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U.S. DEPARTMENT OF ENERGY

Economic Investigation of Community-Scale Versus Building Scale Net-Zero-Energy

N Fernandez
S Katipamula
MR Brambley
TA Reddy

December 2009

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TA Reddy[1]

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[1]Professor, Arizona State University

Executive Summary

Many government and industry organizations are focusing building energy-efficiency goals around producing individual net-zero buildings (nZEBs), using photovoltaic (PV) technology to provide on-site renewable energy after substantially improving the energy efficiency of the buildings themselves. Seeking net-zero energy (NZE) at the community scale instead introduces the possibility of economically using a wider range of renewable energy technologies, such as solar-thermal electricity generation, solar-assisted heating/cooling systems, and wind energy.

This reports documents results of a study comparing NZE communities to communities consisting of individual nZEBs. Five scenarios is examined: 1) base case – a community of nZEBs with roof-mounted PV systems; 2) NZE communities served by wind turbines on leased land; 3) NZE communities served by wind turbines on owned land; 4) communities served by solar-thermal electric generation; and 5) communities served by photovoltaic farms. All buildings are assumed to be highly efficient, e.g., 70% more efficient than current practice.

The scenarios are analyzed for two climate locations (Chicago and Phoenix), and the levelized cost of electricity for the scenarios is compared. The results show that even for the climate in the U.S. most favorable to PV (Phoenix), more cost-effective approaches are available to achieving NZE than the conventional building-level approach (rooftop PV with aggressive building efficiency improvements). The report shows that by expanding the measurement boundary for NZE, a community can take advantage of economies of scale, achieving improved economics, while reaching the same overall energy-performance objective.

The study examines issues concerning whether achieving NZE performance at the community scale provides economic and potentially overall efficiency advantages over strategies focused on individual buildings using a simplified economic analysis. The increased diversity of load, roof and land area available for renewable energy conversion, economies of scale, and variety of renewable energy technologies possible at the community scale suggest that targeting efficiency improvements at this level of aggregation should have distinct practical advantages over pursuing NZE for individual buildings. This study examines these issues considering two locations, Phoenix and Chicago, which experience quite different weather conditions and solar insolation. NZE communities use the same improvements in the efficiency of individual buildings as strategies focused on individual nZEBs. The choice of technology for onsite renewable generation represents the primary difference between these two basic strategies.

While the exact size and makeup of a community for consideration as a NZE community is somewhat arbitrary, care was taken for this analysis to develop a community that matched well with most peoples' concept of what constitutes a typical community. Qualitatively speaking, the community is intended to constitute residential neighborhoods of the size necessary to completely support one high school and one supermarket, as well as a supporting light commercial infrastructure, likely including things like office buildings, small retail, health care, gas stations, and restaurants. The theoretical community is modeled from an existing community in terms of the square footage and general building footprint. An additional specification is that each of the buildings is designed to be a high-performance (HP) building, which consumes 70% less than a typical building (compared to typical U.S. buildings in the Residential Buildings

Energy Consumption Survey (RECS) and the Commercial Buildings Energy Consumption Survey (CBECS).

Five different renewable technology scenarios were considered for the analysis: 1) Base Scenario – A Community of NZEBs, 2) Community-Scale NZE using Wind Turbine (Scenario A), 3) Community-Scale NZE using Wind Turbines (Scenario B), 4) Community-Scale NZE using a Solar-Thermal Electric Plant and 5) Community-Scale NZE using a Solar PV Farm.

The goal in this study is to compare the relative costs of the NZE building concept to the NZE community concept. The analytical methodology used to compare various NZE community and NZE building scenarios started with the specification of a community of high-performance residential and commercial buildings. It is also assumed that the baseline community specification also includes standard electricity distribution infrastructure. Thus, in the cost analysis, it is not necessary to analyze all of the costs that are borne during the construction and operation of the community, only the cost components that are not shared by each scenario. Thus, components such as the construction of the buildings themselves, and the electricity distribution network are left out because these costs are identical from one scenario to the next. It is assumed that in either the NZE community or the NZE building case, the generation will be located within the community, such that there is no need for extra transmission infrastructure.

By comparing generating costs between the two options, the net cost to the community at large of choosing one NZE energy approach over another can be analyzed. Generating costs are presented in this report in terms of $/kWh, combining annualized capital costs and recurring operations and maintenance (O&M) costs into a single levelized cost of electricity generation (LCOE). Capital and O&M costs for electrical generating infrastructure, including renewable energy, are functions of the installed capacity of the generator, and in some cases, the total electric energy produced. The methodology to size the installed capacity of generation involves creating an hourly model of each type of renewable energy generation (each functions of the wind and solar resource as well as other factors like temperature), and solving for the installed capacity size (in kW or MW), for which the annual electric energy generation (the sum of kWh generation from each hour of the year) from all of the renewable energy generators is equal to the annual sum of the electric loads from each of the community's buildings. Because the community is only required to be net-zero energy on an annual basis, and because it is assumed the grid costs are same for buying as well as selling, an hourly model for community loads is not necessary in this analysis framework. Annual electric energy consumption is estimated from the RECS and CBECS databases of existing buildings, with each building in the envisioned high-performance building community being 70% more energy efficient (by floor area) than buildings of corresponding type within the two databases.

For each of the renewable energy technologies analyzed, a simple hourly model was created to estimate hourly electricity production, which was then summed over the course of a year, and matched with the annual community electricity load to size the system to net-zero energy.

The LCOE for each NZE approach for both cities is summarized in Figure E-1. The NZE building scenario using rooftop photovoltaics was the most expensive scenario. For Chicago, however, the LCOE for rooftop PV is about equal to the LCOE for solar-thermal electricity for a community of 16,000 people. This is an interesting result because according to conventional thinking, while not optimally suited for Chicago, rooftop PV would still be a viable technology for those building owners looking to 'go green'. That same conventional thinking, however, would dictate that a solar-thermal plant is a ridiculous idea in a place like Chicago. In reality, however, the costs can be nearly equivalent for powering a NZE community in Chicago for these two technologies. Similarly for Phoenix, in the Arizona desert, it would seem almost criminal to suggest wind power over solar power. Yet, at the default community size, the case of the wind farm on leased land, as inefficient as the wind generation may be, is still more cost-effective than either solar-thermal electric generation or a PV farm at the default community size (let alone rooftop PV, which is more expensive still).

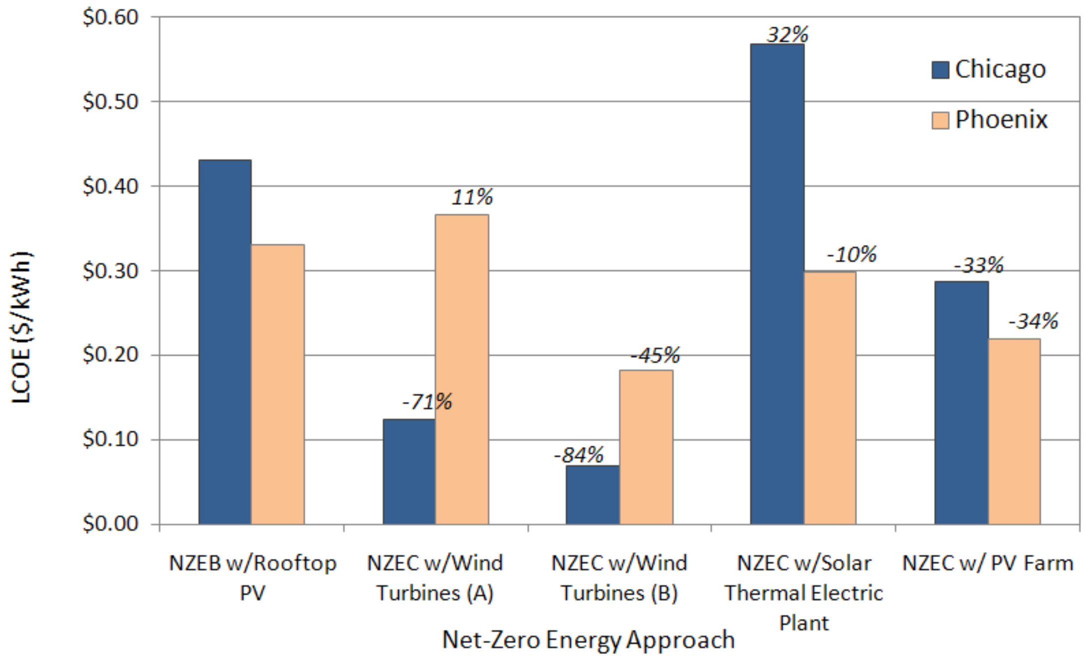

Figure E1 LCOE for Each NZE Approach

Thus, one could argue that conventional thinking may have a bias towards the idea of a nZEB and/or a lack of appreciation for economies of scale. Furthermore, there may be an automatic assumption that a having one more favorable renewable resource endowment means that the most cost-effective solution must utilize that resource. The bias towards nZEBs may have something to do with the idea of liberating the building from external sources of generation, but in a technical sense, this is not true because NZE buildings are still very much dependent on the grid.

Phoenix was chosen for this study because it has such abundant solar resources, and poor wind resources, making it one of the most attractive places for NZE buildings using PV. Thus, what has been shown in this study is that even for the best case in the U.S. for NZE buildings, there are more cost-effective approaches to achieving NZE than the conventional suite of technologies (rooftop PV, with aggressive energy-efficiency measures) used at the building level. By expanding the conceptual boundary for net-zero, a community can take better advantage of economies of scale, as well as having other generation options at its disposal.

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Abbreviations

α	solar absorptivity
AC	alternating current
AIA	America Institute of Architects
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning
amb	ambient
C_i	installation cost
C_o	reference installation cost
CBECS	Commercial Building Energy Consumption Survey
DC	direct current
DOE	Department of Energy
δ	solar declination
ε	thermal emissivity
EUI	energy use intensity
F	fraction
GIS	Geographic Information Systems
h	hourly
HP	High Performance
K_i	installation size
K_o	reference installation size
LCOE	levelized cost of electricity generation
n	day of the year (1-365)
nZEB	net-zero-energy buildings
NZE	net-zero-energy
η	efficiency
η_h	hourly plant efficiency
η_o	efficiency at rated conditions
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
P	power
P_o	power generated at rated conditions
PT	parabolic trough
PV	photovoltaics
Ø	latitude
RECS	Residential Buildings Energy Consumption Survey
σ	Stefan-Boltzmann constant
s	surface
SF	scaling factor
SAM	NREL's Solar Advisor Model
STE	solar-thermal electric
T	temperature
TMY	Typical Meteorological Year
θ	angle of incidence of sunlight with respect to solar collector
θ_{roof}	roof angle with respect to horizontal ground
ω	solar azimuth angle

1. Introduction

Several prominent organizations, including the U.S. Department of Energy (Crawley et al. 2009; US DOE 2008), the State of California (CPUC 2008), and the European Union (European Parliament 2009), have adapted net-zero-energy buildings (nZEB) as strategic targets in their efforts aimed at energy efficiency and sustainability. The vision of nZEBs is also being recognized by building design professional societies such as American Society of Heating Ventilation and Air Conditioning Engineers (ASHRAE) (ASHRAE 2008a, b) and American Institute of Architects (AIA) (AIA 2008). Although definitions of nZEB performance vary (Torcellini et al. 2006), the most widely adopted definition is that an nZEB produces at least as much energy on-site from renewable sources as it consumes from off-site, non-renewable sources over the course of a year. This level of energy performance is achieved by sufficiently reducing the energy needs of the building through efficiency improvements that the balance of energy needed can be supplied with onsite renewable energy technologies.

Seeking net-zero-energy (NZE) at the community scale opens up the possibility of using a variety of renewable generation technologies, such as solar-thermal electricity generation, solar-assisted heating/cooling systems, onsite battery storage, and wind energy. Furthermore, community-scale energy storage might be used cost-effectively to reduce costs by decreasing the demand for peak electric power. These technologies can't be easily deployed in a single home or a commercial building. If the focus is shifted from development of single NZE homes or single NZE commercial buildings to a community-scale NZE, these and other alternate renewable power sources are technically feasible and potentially practical at a community level.

If the push for NZE homes/community is realized, as many organizations hope, it will have significant repercussions on the stability and reliability of the electric grid. It can be expected that the onsite generation technology will introduce additional volatility to the load profile. It is the expected increase in the volatility of a future net-zero load that challenges the transmission and distribution system planning process. Grid operators already expect difficulty to integrate intermittent wind energy into the grid because of the unpredictable nature of the resource and the fact that generation is completely decoupled from load. The introduction of large numbers of NZE homes and buildings is likely to exacerbate the problem of renewable integration if there is not careful planning and recognition of the interactions early on.

The study presented in this report examines issues concerning whether achieving NZE performance at the community scale provides economic and potentially overall efficiency advantages over strategies focused on individual buildings. The increased diversity of load, roof and land area available for renewable energy conversion, economies of scale, and variety of renewable energy technologies possible at the community scale suggest that targeting efficiency improvements at this level of aggregation should have distinct practical advantages over pursuing NZE for individual buildings. This study examines these issues considering two locations, Phoenix and Chicago, which experience quite different weather conditions and solar insolation. Furthermore, local values of land differ, as well as energy prices. A small set of renewable energy technologies is considered—solar photovoltaic (PV), solar-thermal electric generation, and wind electric power—with the results compared to the standard single-building assumption that PV is used to provide the on-site renewable generation. NZE communities use the same improvements in the efficiency of individual buildings as strategies focused on individual nZEBs. The choice of technology for onsite renewable generation represents the primary difference between these two basic strategies.

In the next section a brief summary of the literature review is presented, followed by the description of the community used in comparing the two NZE scenarios in Section 3. Section 4 provides the description of the renewable technologies considered for the various scenarios. The analytic method used in this study is described in Section 5. The results of analyzing the two NZE scenarios with various renewable energy options are described in Section 6. A summary of discussion, conclusion and future work is presented in Section 7, followed by references, bibliography and appendix.

2. Literature Review

Although there is significant interest in nZEBs, much of the nZEB's efforts currently underway are focused towards building individual NZE homes or buildings. Although nZEBs are technically feasible with today's technology in some climate locations (Griffith et al. 2007), significant improvements in efficiency are needed in the renewable generation technologies, as well as the buildings and their systems, for broader adoption of nZEBs. Current practice is to put photovoltaic (PV) cells on rooftops to generate power and in some cases tap into the geothermal sources for heating and cooling needs. For significant penetration of NZE homes and commercial buildings under the current paradigm, cost of the PV technology must be significantly lowered.

Because there are a number of definitions of what a zero-energy goal means, the choice of the definition affects the choices designers make to achieve net-zero. Although there are a number of definition of what constitutes NZE, the most widely adopted definition is that an nZEB produces at least as much energy on-site from renewable sources as it consumes from off-site, sources over the course of 1 year. Torcellini et al. (2006) described four well-documented definitions – net-zero site energy, net-zero source energy, NZE costs, NZE emissions. They applied the four definitions to set of low-energy buildings for which extensive energy data was available and showed how the definition impacts whether or not the building is net-zero.

The establishment and advancement of the Building America program propelled research on NZE home design and technology development. For example, the database of homes built under the Building America research project is now approaching 42,000 (as of December 2009)[2]. In cooperation with the effort, the Department of Energy's national laboratories have published a number of publications addressing the vision for reaching the 2020 goal of marketable zero energy homes. Outside the U. S., Canada is also pushing for zero energy solar homes through its Natural Resources Canada and the Advanced Houses Program.

Griffith et al. (2007) evaluated a large sample of commercial buildings compliant with ASHRAE Standard 90.1 and developed models of them in EnergyPlus. Various simulations were run to see if existing technological improvements could be made to the buildings to achieve NZE. The nZEB goal was found to be achievable for about 62% of commercial building stock (47% of floor area) when applying future performance levels from currently known technologies and design practices.

Christian (2005) describes the efforts in developing near-zero-energy homes in Tennessee. Christian outlines the technologies used in construction and the efforts undertaken to monitor the performance of the four homes for research purposes. Outside of laboratory initiated research and development, Mertz et al. (2005, 2006) evaluated the potential of NZE housing on the campus of the University of Dayton with a conceptual and a cost-benefit analysis. In partnership with Natural Resources Canada, Charron (2005a, b, c, 2006, 2007) evaluated the possibilities of zero-energy solar homes in Canada and the tools necessary for design and optimization. Much

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[2] http://www1.eere.energy.gov/buildings/building_america/

has been reported on the winter heating demands of Canadian homes and the accurately modeling of the thermal mass of a residence using computer simulation tools. Genetic algorithms are being explored as an optimization tool for home design.

Aside from the whole building approach, Biaou and Bernier (2008) focused solely on domestic hot water production and the appropriate technology for achieving NZE with that specific energy demand. Arasteh et al. (2006) examined the importance of appropriate technology in window design in order to achieve NZE. Chasar et al. (2006) analyzed available data from NZE homes in comparison with code compliant homes to determine the energy savings achieved through lowered cooling demands. Lombardi et al. (2004) used the EnergyGauge USA software to determine characteristic photovoltaic production to meet residential building energy demands, which were simulated using DOE-2. Lastly, Dean et al. (2007) introduced the discussion of the effect that occupant energy use has on the viability of achieving NZE homes.

There are also a few community-level NZE efforts underway; for example, a Danish community;[3] Dongtan[4] in Shanghai, China; and a planned city, Masdar, in Abu Dhabi.[5] The Danish community is the only one among the three that is actually fully functional and uses wind turbines for power generation, biomass fueled district heating to meet the heating needs and Canola oil to power a small fraction of their automobiles. Masdar City is a mixed-use community with a combination of residential, commercial and industrial buildings with a goal of being carbon-neutral and waste-neutral. Although both Dongtan and Masdar have been designed, they are still under construction and at this time, it is not clear if they will achieve the carbon-neutral goal.

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[3] http://www.newyorker.com/reporting/2008/07/07/080707fa_fact_kolbert?currentPage=all
[4] http://www.wired.com/wired/archive/15.05/feat_popup.html
[5] http://www.masdar.ae/en/home/index.aspx

3. Description of Community used for Comparison

In this section the description of the community used in comparing the two NZE scenarios is described.

3.1 Strategy/Approach for Developing the Community

While the exact size and makeup of a community for consideration as a NZE community are fairly arbitrary, care was taken for this analysis to develop a theoretical community that matched well with most peoples' concept of what constitutes a typical community. Qualitatively speaking, the community is intended to constitute residential neighborhoods of the size necessary to completely support one high school and one supermarket, as well as a supporting light commercial infrastructure, likely including things like office buildings, small retail, health care, gas stations, and restaurants. The theoretical community is modeled from an existing community in terms of the square footage and general building footprint of the buildings. An additional specification is that each of the buildings is designed to be a high-performance (HP) building, capable of achieving 70% reduction in building energy consumption (compared to typical U.S. buildings in the Residential Buildings Energy Consumption Survey (RECS Public Use Microdata Files , 2005) and the Commercial Buildings Energy Consumption Survey (CBECS Public Use Microdata Files, 2003). The existing community modeled is Wilde Lake in Columbia, MD. This community was selected for the following reasons:

- Columbia is a master-planned city, and Wilde Lake is one of the planned communities within the scope of that development. Thus, the boundaries of the community are well-defined, as opposed to more organic community development, which can be characterized by continuously growing communities with unclear or arbitrary boundaries.

- The website for Howard County, MD (Maps: My Neighborhood, 2009), in which this community is located, contains an interactive Geographic Information Systems (GIS) service that allows a web user to query the owner and top-level construction details of all buildings within each community. This was identified as a tool to estimate the commercial and residential square footage of the community.

A view of the community boundary in Google maps is shown below in Figure 1.

Figure 1: Google Maps Satellite Image of the Wilde Lake Community

3.2 Residential Building Characteristics and Energy Use

Statistics found on the Wilde Lake Community Association website (About Wilde Lake, 2008) were used to find the number of homes of each residential building type within the Wilde Lake community. To determine the average square footage for each building type within the residential sector, 20 different buildings from each building type (single-family detached homes, townhouses, and apartment units) were queried at random using the GIS tool on the Howard County, MD website (Maps: My Neighborhood, 2009). The average square footage from those samples is assumed to be the typical square footage for each household of that type in this community. Table 1summarizes the residential sector.

Table 1: Makeup of the Residential Sector of Wilde Lake

Home Type	Floor Area (square feet)	# in Community	Total Square Footage
Single Family detached	2030	684	1,388,520
Townhouse	1535	440	675,400
Apartment	1223	1494	1,827,162
Total		2618	3,891,082

To estimate the residential building sector's energy consumption, the RECS database (RECS Public Use Microdata Files , 2005) was queried for all 'all-electric' buildings matching a certain building type and a certain climate zone. For Phoenix, the 'Southwest' climate zone is used, and for Chicago, the North-Central climate zone is used. Table 2 shows the energy use intensities (EUIs) for buildings of each residential building type in the climate zone containing each city. The number of building samples available in the RECS database is shown in parenthesis next to each figure. In the column to the right of the RECS data is the EUI for a corresponding HP building.

Table 2: Residential Building Energy Use Intensities (EUIs, kWh/sf/year)

	Chicago		Phoenix	
Building Type	RECS	HP building	RECS	HP building
Detached Home	5.72$_{(95)}$	1.72	6.78$_{(83)}$	2.03
Townhouse	7.60$_{(5)}$	2.28	9.67$_{(3)}$	2.90
Apartment	11.01$_{(32)}$	3.30	13.15$_{(49)}$	3.95

A limitation of this approach is that for some building types in some climate locations, the sample size can be very small for the purpose of determining an accurate value for building energy consumption. In the analysis performed within this work, however, the economics of the NZE community plans are relatively insensitive to individual building energy consumption.

The EUIs for the HP buildings in Table 2 are multiplied by the community total building square footages from Table 1 to calculate the total electricity consumption of the residential sector in Table 3.

Table 3: Residential Sector Energy Demands (kWh electricity/year)

	Chicago	Phoenix
Detached homes	2,383,284	2,823,819
Townhouses	1,539,327	1,960,017
Apartments	6,034,035	7,210,166
Total	9,956,647	11,994,002

3.3 Commercial Building Characteristics and Energy Use

The commercial sector of Wilde Lake is composed of the following sets of buildings:

- 4 medium office buildings (30,000-90,000 square feet)
- 7 small office buildings (< 30,000 square feet)
- 1 shopping center containing 14 strip-mall-sized stores and restaurants, a bank, a gas station, and a community center
- 1 convenience store
- 1 high school, 1 middle school, and 2 elementary schools
- 1interfaith worship center
- 3 neighborhood centers, with day-care nursing facilities for young children.

Each building listed above was assigned a building type, according to the building types categorized in CBECS. EUIs for each building type in each climate for all-electric buildings were obtained in the same way as for the residential sector. They are presented in Table 4 along with the corresponding EUIs for HP buildings. The sample size for each building type in each climate zone is provided in parenthesis next to each EUI figure from CBECS.

Table 4: Commercial Building EUIs (kWh/sf/year)

	Chicago		Phoenix	
Building Type	CBECS	HP building	CBECS	HP building
Food Sales	37.99$_{(6)}$	11.40	61.30$_{(10)}$	18.39
Food Service	47.33$_{(4)}$	14.20	27.59$_{(4)}$	8.28
Public Assembly	14.19$_{(6)}$	4.26	21.73$_{(10)}$	6.52
Education	12.36$_{(11)}$	3.71	13.95$_{(34)}$	4.18
Retail	20.98$_{(9)}$	6.29	20.78$_{(42)}$	6.23
Office	26.55$_{(22)}$	7.97	20.75$_{(58)}$	6.23
Religious Worship	6.48$_{(7)}$	1.94	15.26$_{(10)}$	4.58

The HP building EUIs from Table 4 are multiplied by the building square footages, queried from the Howard County GIS tool to calculate the annual energy consumption of the commercial sector, for Phoenix and Chicago, in Table 5.

Table 5: Commercial Sector Electricity Demands in Chicago and Phoenix

Building Description	Floor Area (Square Feet)	CBECS building Type	kWh/year (Chicago)	kWh/year(Phoenix)
Tall Office Building 1	90,100	Office	717,688	560,880
Tall Office Building 2	90,100	Office	717,688	560,880
Medium Office 1	35,724	Office	284,558	222,385
Small Office 1	9,237	Office	73,577	57,501
Small Office 2	4,954	Office	39,461	30,839
Small Office 3	14,616	Office	116,423	90,986
Small Office 4	31,100	Office	247,726	193,600
Small Office 5	28,480	Office	226,856	177,290
Small Office 6	13,606	Office	108,378	84,698
Small Office 7	8,000	Office	63,724	49,801
Small Office 8	5,704	Office	45,435	35,508
Sporting Goods Store	9,756	Retail	61,410	60,822
Convenience Store	3,132	Food Sales	35,692	57,602
Strip Mall: Karate	1,700	Retail	10,701	10,598
Strip Mall: Liquor Store	1,700	Retail	10,701	10,598
Strip Mall: Nail Salon	1,700	Retail	10,701	10,598
Strip Mall: Barber Shop	1,700	Retail	10,701	10,598
Strip Mall: Gas Station	9,000	Retail	56,651	56,109
Strip Mall: Dry Cleaner	1,700	Retail	10,701	10,598
Strip Mall: Parcel Store	1,700	Retail	10,701	10,598
Strip Mall: Pharmacy	3,000	Retail	18,884	18,703
Strip Mall: Bank	9,000	Retail	56,651	56,109
Strip Mall: Organic	10,000	Food Sales	113,958	183,913
Strip Mall: Seafood	3,000	Food Sales	34,187	55,174
Strip Mall: Café	3,000	Food Service	42,598	24,834
Strip Mall: Restaurant 1	3,000	Food Service	42,598	24,834
Strip Mall: Restaurant 2	1,700	Food Service	24,139	14,073
Strip Mall: Restaurant 3	2,250	Food Service	31,949	18,626
Strip Mall: Restaurant 4	7,750	Food Service	110,046	64,155
Interfaith Worship	30,000	Religious Worship	58,344	137,362
High School	240,000	Education	890,009	1,004,311
Middle School	90,000	Education	333,753	376,616
Elementary School 1	70,000	Education	259,586	292,924
Elementary School 2	70,000	Education	259,586	292,924
Community Gathering	37,000	Public Assembly	157,495	241,237
Village Center 1	5,000	Public Assembly	21,283	32,600
Village Center 2	5,000	Public Assembly	21,283	32,600
Village Center 3	5,000	Public Assembly	21,283	32,600
Community Total	958,409		5,357,102	5,206,083

4. Renewable Technology Scenarios Considered

In this section, the renewable technologies considered for the various scenarios are described.

4.1 The Base Scenario – A Community of NZEBs

The base scenario is meant to embody what a whole community of nZEBs would look like. The buildings themselves are HP buildings that achieve 70% reduction in energy consumption over the current national average for that building type, and use electricity for all building energy consumption. The only generation technology available onsite to each building in the community is roof-mounted PV. For some building types, rooftop PV will not satisfy all of the building electricity requirements, even for these HP buildings. In this analysis, these buildings simply fail to meet NZE status. This does not have any effect on the economic analysis, however, because it is done on a $/kWh basis. Community costs unique to this scenario include the full installation cost of the PV panels and inverters, plus maintenance/cleaning costs required to keep electricity production at expected levels.

4.2 Community-Scale NZE using Wind Turbines (Scenario A)

In this scenario, the buildings are the same as in the base scenario, except without rooftop PV. Wind turbines are used to achieve NZE status for the community as a whole. Land for the entire wind farm is purchased at rates typical of the median rate for the outer suburbs of the city being analyzed (since this is where development is likely). Community costs unique to this scenario include the full installed cost of the wind turbines, operations and maintenance (O&M) costs for the wind farm, land purchase costs, and net metering credits (because a discrete number of wind turbines must be purchased, the community ends up producing slightly more than it consumes, so the difference is sold back to the grid at the mean 2008 wholesale electricity price for its region).

4.3 Community-Scale NZE using Wind Turbines (Scenario B)

In this scenario, land required for the site of each turbine base is leased from local farms or private landowners, as is typical in situations where all land in the vicinity of a proposed wind site is pre-owned or prices for land ownership are prohibitively expensive. The details of the leasing arrangement are set according to the arrangement described in (Area Farmer Doesn't Mind Wind Turbines on His Land, 2009), and the rental costs set according to the relative land value between the site described in the article and the proposed sites in Phoenix and Chicago. Community costs unique to this scenario include the full installed cost of the wind turbines, O&M costs for the wind farm, land rental costs, and net metering credits. Costs associated with the dismantling of the wind farm at the termination of the lease and credits associated with its recycling thereafter are neglected.

4.4 Community-Scale NZE using a Solar Thermal Electric Plant

In this scenario, a parabolic trough, concentrating solar-thermal plant is designed and scaled to achieve NZE status for the community. The troughs are on a single-axis tracking system, aligned N-S. The plant is built on additional land purchased and used solely by the plant. Community costs unique to this scenario include the full installed cost of the solar-thermal plant, O&M costs for the plant, and land purchase costs. A parabolic trough plant was selected for this analysis because it is the most mature utility-scale solar-thermal technology, with the most available cost data.

4.5 Community-Scale NZE using a Solar PV Farm

In this scenario, a solar farm is designed and scaled to achieve NZE status for the community. The panels are designed as fixed structures, set at a 35° angle with respect to the ground. The plant is built on additional land purchased and used solely by the farm. Community costs unique to this scenario include the full installed cost of the PV farm, O&M costs for the farm, and land purchase costs.

5. Analytic Method

The goal in this report is to compare the relative costs of the NZE building concept to the NZE community concept. To accomplish this, we are comparing the community of NZE buildings to several identical communities that are NZE as a whole. Thus, in the cost analysis, it is not necessary to analyze all of the costs that are borne during the construction and operation of the community, only the cost components that are not shared by each scenario. Thus, components such as the construction of the buildings themselves, and the electricity distribution network are left out because these costs are identical from one scenario to the next. The total of the unique costs for each scenario represents the total levelized cost of electricity generation (LCOE) for that scenario.

Factors including the community makeup, its location, and the prices for the individual technologies affect the LCOE. Building-energy demands affect the size of the PV system required for each building for the NZE building base case, and affect the size of the community-scale generation system for each of the comparative cases. The building level and community level generation sizing affects the levelized cost of electricity through economies of scale. The community's location dictates the renewable resources available, and hence the capacity of the system required to generate enough energy to achieve NZE status. When a higher system capacity is required to **serve** the same load, capital O&M and land costs generally increase. This is why renewable technologies in less favorable geographic locations are more expensive on a $/kWh basis. Some technologies are less expensive to produce and install per rated power production, which also affects the cost of energy production for the community. The techniques for analyzing each of these factors are described in detail in this section.

5.1 Modeling Renewable Energy Systems

In this section, the modeling framework for analyzing the energy production from PV panels, wind turbines and parabolic trough solar-thermal electric plants is discussed, along with the performance assumptions that were used. An Excel spreadsheet program developed for this analysis is used for the modeling.

5.1.1 – Rooftop Photovoltaic (PV)

Rooftop PV in the NZE building scenario is modeled on an hourly basis over the course of the year in each location. A sample PV module (BP Solar SX 3190B) was selected for this analysis based on its highly competitive price online ($3.10/watt; Beyond Oil Solar, 2009), and its high DC conversion efficiency (15.01%). This peak conversion efficiency was calculated based on the manufacturer's specified peak power (SX 3195, 2009), the gross area of the panel, and the insolation at the standard PV test condition used in the specification (1000 W/m^2, 25°C module temperature).

The first step in this analysis is to investigate the hourly insolation on the surfaces of interest in each location. For all commercial buildings, the surface is a flat plane parallel to the ground. For all residential buildings, it is a sloped roof surface. We assume that the slope of all of the residential roofs is 35° with respect to flat ground, and that the houses will be built with a single-sloping roof with a surface azimuth of 0° (pointing south) to fully take advantage of solar insolation for electricity generation. To calculate insolation on those two sets of surfaces, a simple Energy Plus model is used, with the output file set up to report hourly surface insolation, using Phoenix-Sky Harbor and Chicago-O'Hare TYM2 (Typical Metrological Year version 2) weather files (National Solar Radiaiton Database, 2009).

With surface insolation calculated, the next step is to estimate the hourly DC conversion efficiency and the resulting DC power generated per square meter. The temperature coefficient of power for this module is -0.5%/K; therefore, we can expect the instantaneous power to be

$$P_{PV} = P_o \cdot [1 - 0.005(T_s - 25)] \quad (1)$$

where P_o is the DC power at the standard PV test conditions, and T_s is the surface temperature of the panel. Similarly, the instantaneous efficiency is given by

$$\eta = \eta_o \cdot [1 - 0.005(T_s - 25)] \quad (2)$$

where η_o is the rated DC efficiency.

An hourly quasi-steady state model was used to estimate the surface temperature of the module, based on the outdoor air temperature, the wind speed, the solar insolation on the panels, and a few assumed optical properties of the panels. The model assumes that the panel is installed on a well-insulated roof, and that the absorbed heat from the solar insolation is balanced only by convection and radiation from the top surface of the panel. Thus, the heat balance equation on the PV panel is:

$$\alpha P_{insolation} = \varepsilon\sigma(T_s^{\,4} - T_{sky}^{\,4}) + h(T_s - T_{amb}) \quad (3)$$

Where α is the fraction of incoming solar radiation that is absorbed as heat (not the entire absorbed solar radiation, because a fraction is converted to electricity), assumed to be 0.7, ε is the thermal emissivity of the panel, assumed to be 0.7, T_{sky} is the effective sky temperature for radiation, assumed to be 15K below ambient temperature, and h is the convective heat transfer coefficient. The linear correlation for h (in W/m^2•K) shown in Equation 4 was used, calculated from Figure 10 of (Clear et al. 2002) for the outside convective air film coefficient for horizontal roofs.

$$h = 7 + 1.42 \cdot v_{(m/s)} \quad (4)$$

where v is the wind speed. The temperature coefficient of power has the effect of reducing the actual overall DC efficiency from the rated efficiency to the levels shown in Table 6.

Table 6: Annual Average PV Panel DC Efficiency for BP Solar SX 3190B Panel

	Chicago	Phoenix
Flat Roof	0.1447	0.1303
Sloped Roof	0.1431	0.1281

Once the hourly DC power is calculated, the next step is to derate the DC power to the level of AC power available on-site (this will be henceforth referred to as the building's power generation). For this estimation, National Renewable Energy Laboratory's (NREL's) program 'PV Watts' was used (PV Watts Version 1 Calculator, 2009). The values in Figure 2 were used for each of the power losses associated with real PV systems, with an overall DC to AC derate factor of 0.729.

Calculator for Overall DC to AC Derate Factor

Component Derate Factors	Component Derate Values	Range of Acceptable Values
PV module nameplate DC rating	1	0.80 - 1.05
Inverter and Transformer	0.92	0.88 - 0.96
Mismatch	0.98	0.97 - 0.995
Diodes and connections	0.995	0.99 - 0.997
DC wiring	0.98	0.97 - 0.99
AC wiring	0.99	0.98 - 0.993
Soiling	0.95	0.30 - 0.995
System availability	0.98	0.00 - 0.995
Shading	1.00	0.00 - 1.00
Sun-tracking	1.00	0.95 - 1.00
Age	0.9	0.70 - 1.00
Overall DC to AC derate factor	**0.729**	

Comments
Assume panel DC Rating is accurate
Middle of prescribed range
Middle of prescribed range
Middle of prescribed range
Middle of Prescribed range
Middle of Prescribed Range
Assume panels are kept mostly clean

Panels always available
No shading on any panels
N/A, not a tracking system
Program prescribes 0.9 for 11th year of operation

Figure 2: 'PV Watts' Screenshot Showing Assumptions Made for DC to AC Derate Factor

The installed nameplate power (kW) required for the building to be NZE can be calculated, according to the equation:

$$P_{rated,\,PV} = \frac{Building\ Demand_{\ (kWh/year)} \cdot 1.00\ kW_{rated} / m^2 \cdot \eta_o}{Generation_{\ (kWh/m^2 \cdot year)}} \tag{5}$$

And the required roof area in m^2 is simply

$$A_{required} = \frac{Building\ Demand_{\ (kWh/year)}}{Generation_{\ (kWh/m^2 \cdot year)}} \tag{6}$$

However, the available rooftop area for PV is

$$A_{available\ (m^2)} = \frac{Total\ Floor\ Area_{(m^2)}}{\#of\ Stories \cdot \cos(\theta_{roof})} \tag{7}$$

where θ is the slope of the roof. If the required PV area is greater than the available area for PV for a building, the PV system is designed to use the entire roof area, but will not produce enough energy to make the building NZE, in this case.

5.1.2 – Wind Power

Like the rooftop photovoltaics, wind turbines are likewise modeled on an hourly basis to provide an estimation of the wind power generated. This modeling required an accurate estimation of the wind speed at the hub height of the wind turbine. Tester et al. (2005) recommended the following equation for the variation of wind speed above an idealized smooth surface:

$$\left(\frac{v_2}{v_1}\right) = \left(\frac{h_2}{h_1}\right)^{1/7} \tag{8}$$

In this equation, h_2 represents the hub height of the turbine, while h_1 is the height above ground level at which the measurements of wind speed were taken. For U.S. weather stations, this height is 10 m. Thus, this equation was used to correct the wind speeds in the TMY2 weather files for Phoenix and Chicago to the hub heights of the turbines investigated.

Five wind turbines were analyzed to compare their relative performance, using manufacturer's supplied power curves for the turbines in each location. These power curves were replicated within the Excel model, and used to predict hourly performance. Of the five turbines (listed in Table 7), the GE[6] XLE 1.5 turbine showed the strongest performance in both locations, with capacity factors[7] exceeding those of the other turbines. In terms of the shape of the power curve, the reason for the higher capacity factors is a lower cut-in and a lower rated wind speed. The power curve for the GE XLE 1.5 turbine is shown in Figure 3. The resulting capacity factor of 0.36 in Chicago matches well with the average capacity factor of 0.33 in 2008 for wind turbines installed in the Great Lakes region from 2004-2007 (Wiser and Bolinger, 2009). This wind turbine was thus selected for the community, because it represented a very competitively performing turbine.

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[6] Use of trade or company names does not constitute endorsement by the authors or the Laboratory.

[7] The capacity factor is the actual annual electric energy generation divided by the annual electric energy generation at the rated capacity.

Table 7: Selected Wind Turbine Specifications, Power Curve and Performance

Wind Turbine Specifications				Power Curve			Capacity Factor	
Name	Rated Capacity [MW]	Hub Height [m]	Rotor Ø [m]	Cut-in Wind Speed [m/s]	50% Power Wind Speed [m/s]	Rated Wind Speed [m/s]	Phoenix	Chicago
GE 2.5[8]	2.5	85	100	3	9	13	0.074	0.268
GE 1.5 XLE[9]	1.5	67	80	3	7.5	11.25	0.12	0.36
Vestas V42[10]	0.6	40	42	4.5	10	15.5	0.033	0.165
Vestas V27[11]	0.225	25	27	3.5	10	0	0.034	0.157
Liberty 2.5[12]	2.5	80	96.4	3	8	13	0.081	0.283

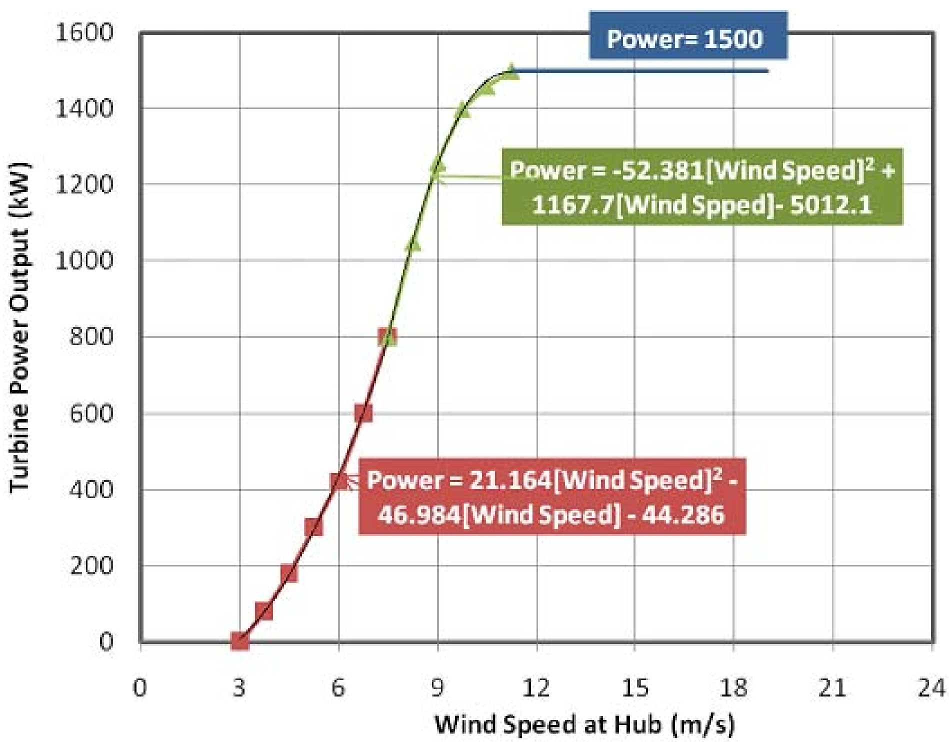

Figure 3: Power Curve for GE 1.5 XLE Wind Turbine, with Superimposed Equations used for Modeling (data for the curves extracted from GE 2009)

The required wind farm capacity is given by Equation 9:

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[8] (GE 2009)
[9] (GE 2009)
[10] (Platte River Power Authority 2009)
[11] (J.P. Slayer and Associates, Consultants Ltd. 2009)
[12] (Clipper Windpower 2009)

$$Capacity_{wind\ farm} = \frac{Community\ Energy\ Demand_{(kWh)}}{Capacity\ \ Factor \cdot 8760_{(hours/year)}} \quad (9)$$

To find the necessary number of turbines to achieve NZE status for the community, the required wind farm capacity must be rounded up to the nearest multiple of 1.5 MW to reflect the existence of a discrete number of 1.5-MW wind turbines.

5.1.3. Solar Thermal Electric Plant

A solar-thermal electric plant is much more complicated to model than a PV panel or a wind turbine, and because there are relatively few commissioned plants operating around the world, it is difficult to find reliable operating data. With this in mind, a simple model of a parabolic trough solar-thermal plant was constructed, based on limited data and a few assumptions.

For the collectors themselves, a N-S axis of orientation was selected for a one-axis tracking system, for which Equation 10 was adopted from Duffie and Beckman (1980) to calculate the angle of incidence of the sunlight, θ with respect to the collectors at each hour of the day.

$$\cos(\theta) = [(\sin\phi \cdot \sin\delta + \cos\phi \cdot \cos\omega \cdot \cos\delta)^2 + \cos^2\delta \sin^2\omega]^{1/2} \quad (10)$$

In this equation, ω is the solar azimuth angle, ϕ is the latitude, and δ is the solar declination, equal to

$$\delta = -23.45^\circ \cdot \sin\left(\frac{360^\circ \cdot (284+n)}{365}\right) \quad (11)$$

where n is the day of the year.

Tester et al. (2005), report that the conversion efficiency for state-of-the-art parabolic trough concentrators is around 12%. This value includes all losses from the mirrors to the grid, so no other reduction factors need be applied. Because the only existing parabolic trough collectors are located where annual direct solar insolation is very intense, it was assumed that 12% is valid for the Nevada Desert. Specifically, the TMY2 location of Yucca Flats in the Nevada desert was chosen as a representative location to calibrate the model. The model assumes that there is no thermal storage from hour-to-hour and that the temperature of the steam entering the turbine varies linearly from ambient temperature (no direct sunlight) to ambient temperature + 375K (950 W/m^2 direct sunlight). The value of 375K was chosen to produce a maximum steam temperature of roughly 400°C, which is the upper end of the temperature range for parabolic trough collectors (Tester et al. 2005). It was further assumed that all losses from the plant amount to a constant fraction (F_{losses}) of the Carnot efficiency, according to Equation 12.

$$\eta_h = F_{losses} \cdot \eta_{carnot} \quad (12)$$

where η_h is the hourly plant efficiency, and

$$\eta_{carnot} = 1 - \frac{T_{ambient}}{T_{steam}} \tag{13}$$

The average annual plant efficiency was calculated according to Equation 14,

$$\eta_{annual} = \frac{\sum_{h=1}^{8760} \eta_h \cdot P_{direct,h}}{\sum_{h=1}^{8760} P_{direct,h}} \tag{14}$$

where $P_{direct,h}$ is the annual direct solar insolation. With this system of equations, F_{losses} could be calculated from a known η_{annual}. When calibrated at the Yucca Flats weather site, a value of 0.26 for F_{losses} was found for η_{annual} of 12%. When applied to the Chicago and Phoenix weather files, the model predicts an η_{annual} of 9.9% for Chicago and 11.7% for Phoenix. These plant efficiencies are then applied to the sum of the annual direct insolation values (on the projected area of the collector surface) over the course of the year to scale the plant to the rated capacity ($P_{rated,PT}$, in MW, for direct insolation of 950 W/m^2) necessary to achieve NZE status. This was done according to Equation 15, using Flosses = 0.26 to calculate η_h.

$$P_{rated,PT} = \frac{Community\ Demand_{(kWh/year)} \cdot 950_{(W_{ins,rated}/m^2)} \cdot \eta_o}{\sum_{h=1}^{8760} (\eta_h \cdot P_{direct,h})_{(kWh/m^2)} \cdot 10^6{}_{(W_{rated}/MW_{rated})}} \tag{15}$$

where η_o is the efficiency at the rated direct solar insolation, and is approximately equal to 14.6%.

5.1.4. Solar PV Farm

The solar PV farm uses the same 35° tilted, south facing panels as those used on the residential buildings in the NZE building scenarios, thus using many of the same equations and assumptions. An alternative is to use a two-axis tracking system, but it is unclear how this would affect the installed cost of the system.

5.2 Land Requirements

While the community of NZE buildings requires no additional land for the community electricity generation, each of the other scenarios requires land, for which the purchase price adds a significant contribution to the levelized price of generated electricity. To estimate land area for the NZE community, the following assumptions are made:

- For Wind Turbine Scenario A, where the land is leased from nearby farms, ½ acre is required per turbine (Area Farmer Doesn't Mind Wind Turbines on His Land 2009)

- For Wind Turbine Scenario B, where land for the entire wind farm is purchased outright, a turbine spacing of 3 turbine rotor diameters per row, and 10 turbine rotor diameters between rows is assumed (New York State Energy Research and Development Authority 2005). Thus, for each turbine, an area equal to 30 square rotor diameters is required.

- For the parabolic trough solar-thermal plant, the plant area is assumed to consist of rows of parabolic troughs, as modeled in Section 5.2, plus aisles between the troughs (to allow maintenance and prevent shadowing) that are 1½ times the width of the troughs themselves. This is based on a visual estimation from a satellite photo of the Nevada Solar One plant, shown in Figure 4, which uses N-S axis troughs.

- For the solar farm, it is assumed that the farm area consists of rows of tilted solar panels, plus aisles between the panels that are equal in width to full width the panels.

Figure 4: Google Maps image of the Northeast Corner of the Nevada One Parabolic Trough Solar Thermal Plant

5.3 Costs

This section describes the methodology for estimating the costs associated with each of the technologies in each scenario.

5.3.1 – Solar Photovoltaic Costs

Installed costs (in $\$/W_{rated}$) of solar photovoltaics are assumed to be a function only of the size of the installation. Other factors, such as the specifics of an installation, the quality of the panel and its manufacturer, may affect installed costs for individual installations, but these are neglected and the average full installation cost is estimated using data for different size ranges, across many orders of magnitude of installation size.

A database is available of almost 25,000 PV installations across the state of California from 2007-2009 (California Energy Commission 2009). This database comprises 75% of the U.S market for solar PV, and is divided into two categories: residential and small commercial (< 10kW), and large commercial (> 10kW). Figure 5 and Figure 6 show a line relating the total installed cost of the PV system plotted against the installation size for all installations in the database. The x-axis on each graph is a logarithmic scale.

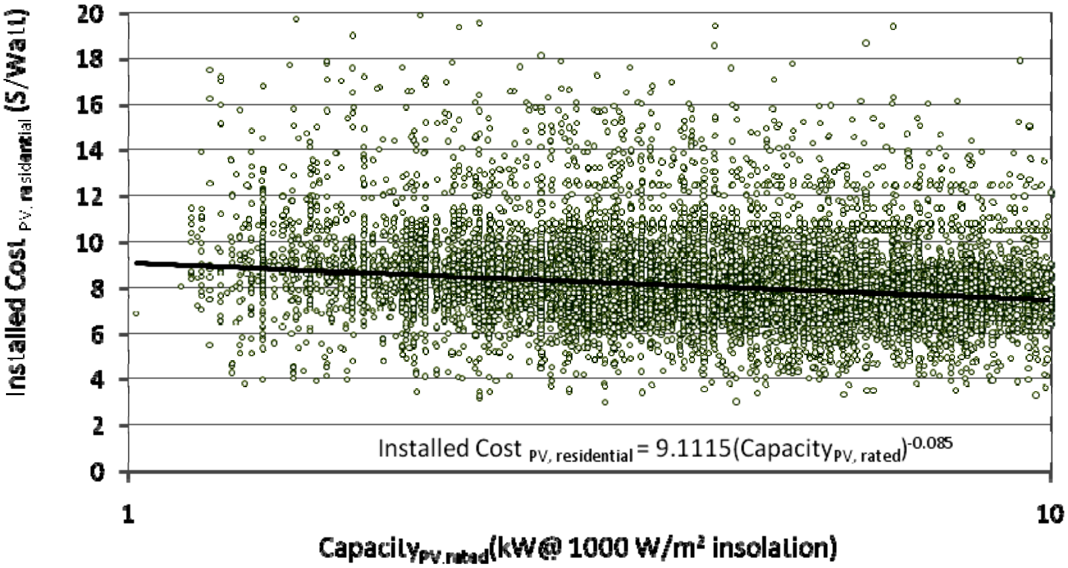

Figure 5: Residential and Small Commercial (<10 kW) PV Systems Installed in California, 2007-2009

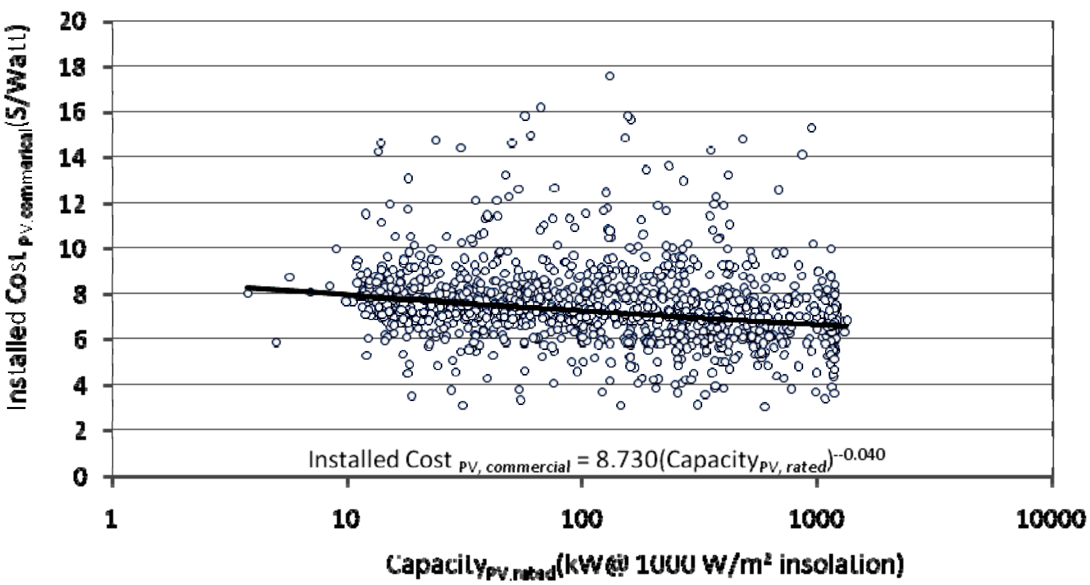

Figure 6: Figure 4: Large Commercial (>=10 kW) PV Systems Installed in California, 2007-2009

To extend PV installation costs to the size of utility-scale systems, project costs for 7 of the 48 existing solar photovoltaic power stations around the world are shown in
Table 8, in $US2009 /peak rated Watt, determined using annual average U.S.-Euro exchange rates and U.S. inflation rates, when applicable.

Table 8: Installation Costs for Utility-Scale PV Systems

Name	Date of Installation	Location	Cost Euro, when built	Cost U.S., when built	Cost (U.S. 2009)	Capacity (MW)	$/W
Moura Station[13]	2008	Spain	€ 250,000,000	$368,150,000	$367,349,274	64	$5.74
Waldpolenz Station[7]	2008	Germany	€ 130,000,000	$191,438,000	$191,021,622	40	$4.78
Erlasee Station[7]	2008	Germany	€ 37,000,000	$54,486,200	$54,367,693	12	$4.53
Monte Alto Station[7]	2007	Spain	€ 65,000,000	$89,121,500	$92,351,376	10	$9.67
Rote Jahne Station[7]	2007	Germany	€ 21,000,000	$28,793,100	$29,836,598	6	$4.97
Nellis AFB[7]	2007	U.S. Nevada	Not Applicable	$100,000,000	$103,624,126	14	$7.40
Cantil Solar Farm[14]	2009	U.S. California	Not Applicable	$11,000,000	$11,000,000	3	$3.23

The residential, commercial, and utility-scale PV installations are combined into one graph (Figure 7) to estimate an economy of scale equation for PV. The residential and commercial trend lines from the database are converted to data points at a density of 5 points per order of magnitude in installation size, to give them equal weight with the utility-scale installations, of which there were many fewer data points.

An equation of the form:

$$\frac{C_i}{C_o} = \left(\frac{K_i}{K_o}\right)^n \qquad (16)$$

is recommended by Tester et al. (2005) for economy of scale equations, where K_i is the installation size of interest, K_o is a reference installation size, C_i is the installation cost of interest, and C_o is the installation cost of the reference installation.

[13] Source: (Wikipedia, 2009)
[14] Source: (Solar Daily, 2009)

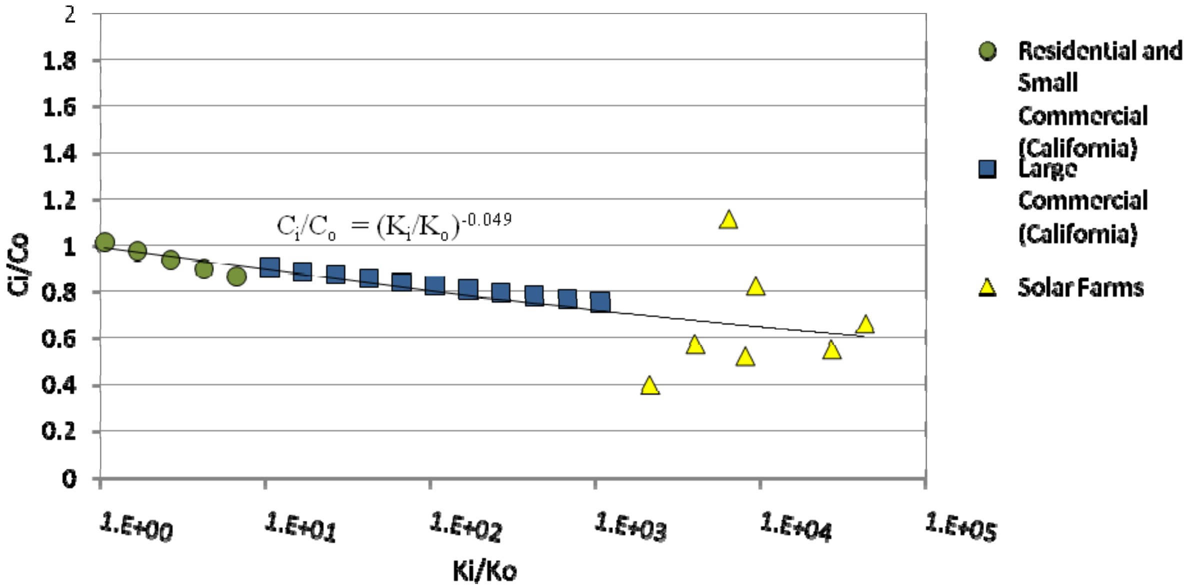

Figure 7: Development of 'Economy of Scale' Equation for Solar PV

Setting 1.5 kW as K_o (with a corresponding installed cost of \$8.65/Watt), Equation 17 gives the economy of scale equation for the installed cost of PV.

$$Installed\ Cost_{PV\ (\$US,2009/W)} = \$8.65 \cdot \left(\frac{K_i}{1.5kW}\right)^{-0.049} \tag{17}$$

O&M costs of rooftop PV systems (which include the necessary cleaning to keep them performing near their capacity) are given in NREL's 'Solar Advisor Model' (Solar Advisor Model 2009), which is a program designed to be a cost simulation tool for the development of different types of solar plants. The default value of \$17.69/kW/year is used for commercial PV systems and \$74/kW/year for residential systems.

5.3.2 – Wind Turbine Costs

Wiser and Bolinger (2009) identify the drivers to the installed cost and the O&M costs of wind turbines in recent years. The most up-to-date installed cost information shows that wind turbines in 2008 cost, on average, \$1915/kW. This is the raw cost before any incentives, which usually take the form of tax credits. The database from which the report was developed contains confidential cost information for specific projects, which we were not able to use in this report. However, according to the report's lead author, Ryan Wiser[15], there does not appear to be any correlation between the size of the installation (for a constant turbine size) and the installed cost per kW. This reflects the highly modular nature of wind farm construction and is supported also by the data shown in Figure 8. The three data series shown do not appear to be statistically different from one another. Thus, no economy of scale equation was applied to the 2008 average

[15] Personal communication, on 7/7/2009

turbine cost. While economies of scale are known to exist based on the turbine size, the relationship is unknown. With that in mind, the selected turbine size for the community is 1.5 kW, which is by far the most common size for wind turbines installed in the last 3 years. In 2008, the average turbine size was 1.67 kW. Thus, the $1915/ kW is likely strongly weighted by cost data from 1.5 kW wind turbines, and this figure is used in this report as a constant for the installed wind turbine cost.

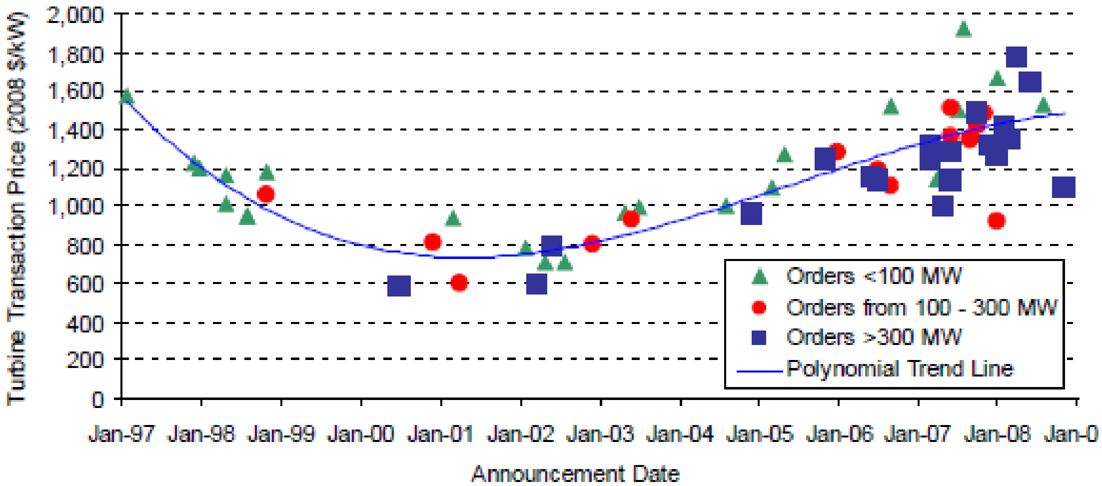

Figure 8: Turbine Transaction Price in $US 2008, as a Function of Time and Order Size Source: Wiser and Bolinger (2009)

O&M costs, on the other hand, do appear to show economies of scale with the size of the installation. Figure 9, reproduced from Wiser and Bolinger (2009), shows that smaller farms have higher O&M costs on a $/kW basis.

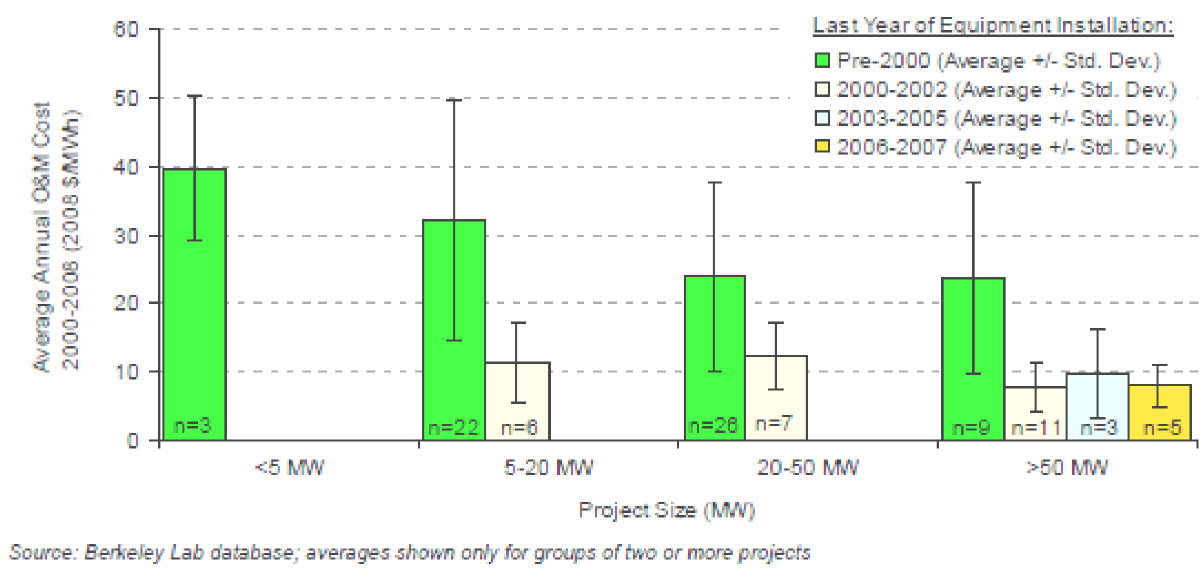

Figure 9: Turbine O&M Costs as a Function of Installation Date and Project Size Source: Wiser and Bolinger (2009)

Figure 10 shows that pre-2000-built turbines have O&M costs that average around $0.02/kWh over the observed maintenance lifetime of the project. This is the case for the pre-2000 data set, which is the only set with data beyond the third year after installation. Additionally, newer turbines (2003 and later) appear to have O&M costs about 40% lower than the pre-2000 turbines during corresponding years since installation. Thus, a rate of $0.012/kWh is assumed as the baseline cost for O&M for new projects.

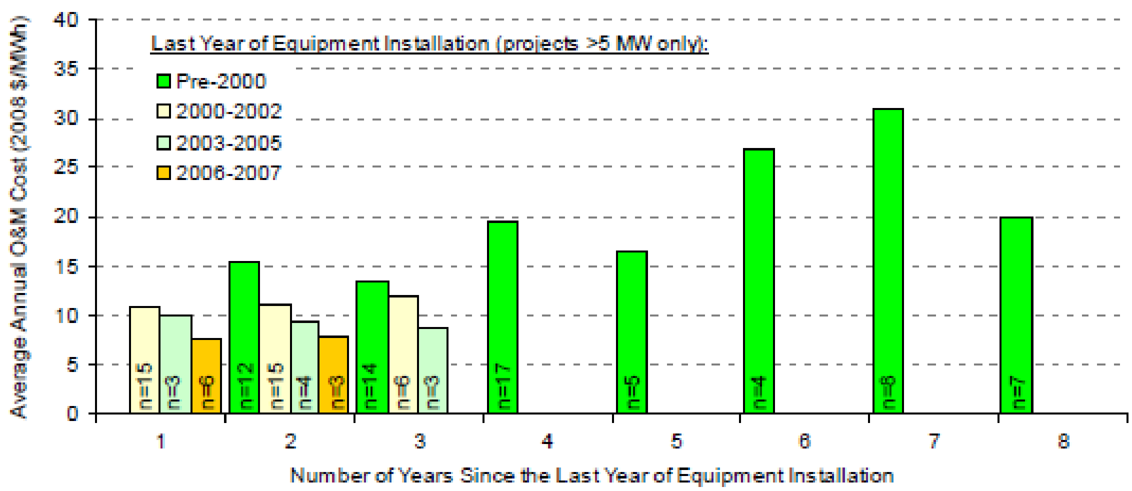

Figure 10: Turbine O&M Prices as a Function of Installation Date and Number of Years Since the Last Year of Equipment Installation Source: Wiser and Bolinger (2009)

A wind farm O&M cost scaling factor ($SF_{wind,O\&M}$) is derived as follows: First, costs from each project size category, and for each installation year set in Figure 9 are divided by the overall average O&M cost in the corresponding installation year set they belong to. This is shown in the red and green data series in Figure 11. The relationship among all installation year sets is then determined by taking the weighted average (by sample size) of the multipliers in each project size category. This is shown in the blue data series in Figure 11. The two most recent installation year sets from Figure 9 only have data for large projects, so the relationship between O&M costs and project size is indeterminate, and they are omitted from the analysis. The data points in Figure 11 are plotted at the center of their project size range. For the large projects category, for the purpose of calculating the wind farm scaling factor equation, it is assumed that the average size in this category is 100 MW. The graph used for the derivation of this equation is shown in Figure 11, with horizontal error bars used to show the project size range in each category.

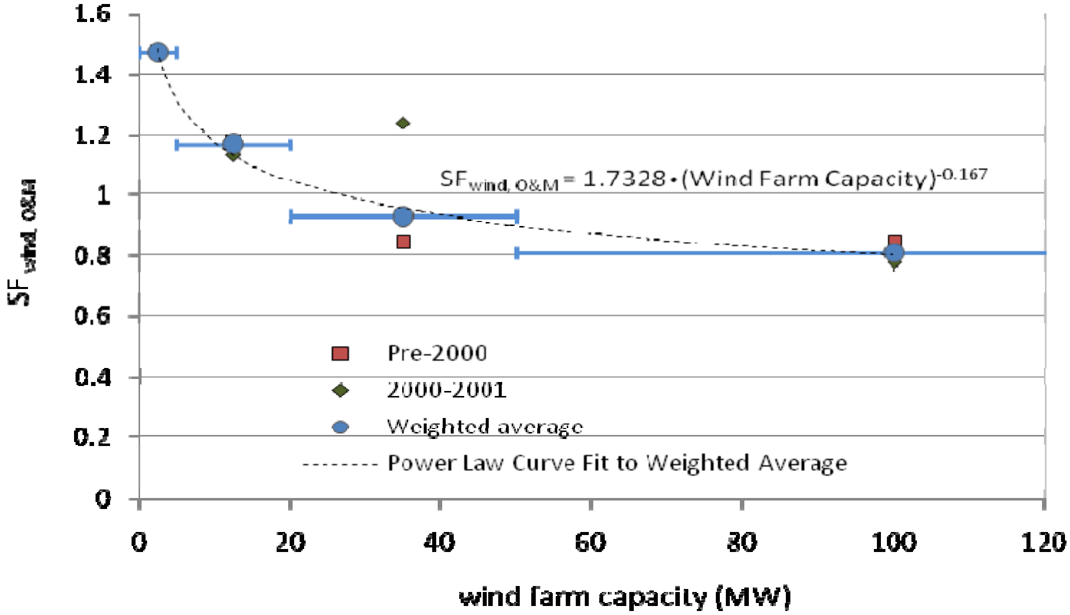

Figure 11: Scaling Factor for Wind O&M Costs

From Figure 11, a scaling factor to the nominal $0.012/kWh is proposed as

$$SF_{wind,O\&M} = 1.73 \cdot Farm\ Size_{(MW)}^{-0.167} \tag{18}$$

5.3.3 – Solar Thermal Electric Plant Costs

Solar thermal electric plants strongly benefit from economies of scale. Price (2002) reports the typical LCOE of solar-thermal electric plants as a function of the rated capacity, $Capacity_{STE}$ (MW). In Figure 12, the reported LCOE values from Price (2002) were normalized to scaling factor, SF_{STE}, normalized to a value of 1 for a 50 MW_e rated plant, and plotted as red points.

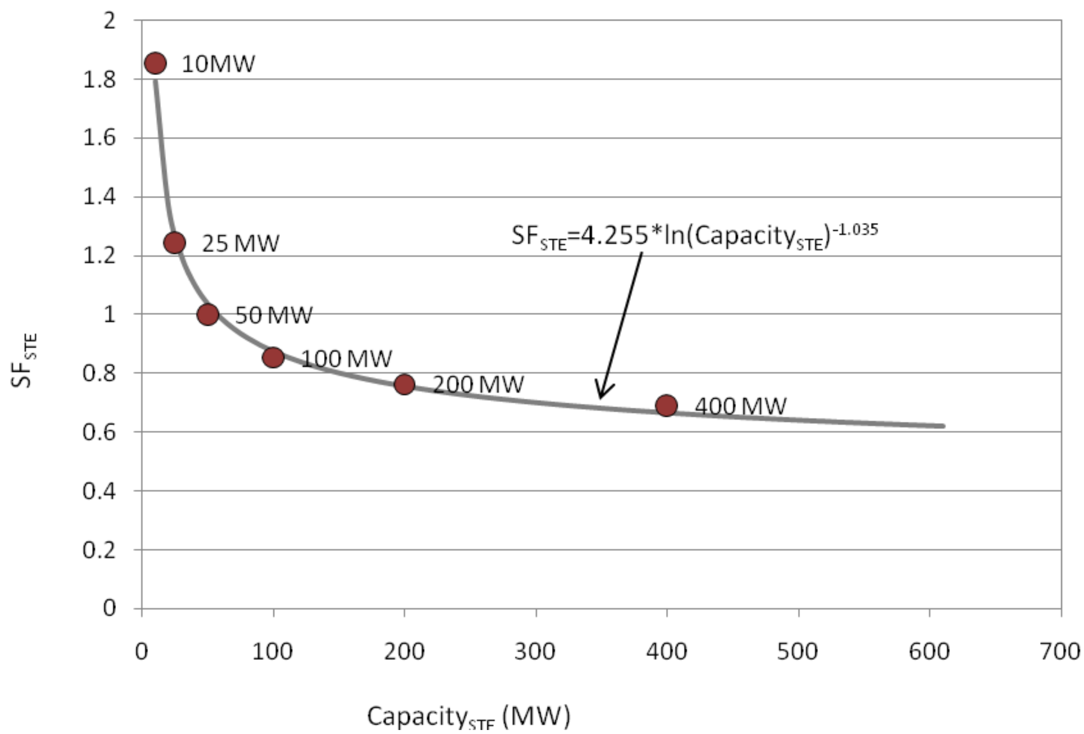

Figure 12: Economy of Scale for Levelized Electricity Cost from Solar Thermal Electric Plants Source: Data for the Chart is from Price (2002)

Using these numbers, an equation is derived to estimate an economy of scale correction factor based on the size of a solar-thermal plant (Equation 19). The derived equation is also shown in Figure 12 as a gray line.

$$SF_{STE} = \frac{LCOE_{Capital,O\&M}}{LCOE_{Capiral,O\&M,50MWplant}} = 4.255 \cdot \ln(Capacity_{STE})^{-1.035} \tag{19}$$

The remaining task was to find the nominal cost ($/kW for a 50-MW plant) to apply this correction factor to.

NREL's SAM program comes with a set of default cost values for a 100-MW parabolic-trough plant. For a plant without thermal storage, the installed cost, not including land purchase, is about $4500/kW$_e$. Using Equation 17 for the economy of scale curve, this corresponds to $5137/kW for a 50-MW plant. In addition to SAM, two other sources were found to estimate installed costs. Stoddard et al. (2006) estimated the economics of a concentrating solar-thermal plant in California, reporting an installed cost of $4802/kW for a 100-MW plant, excluding thermal storage (converted here to $2009). This corresponds to $5482/kW for a 50-MW plant. The 64-MW Nevada Solar One Power plant cost $266 million (Solar Paces, 2007), which is $4307/kW when converted to $2009. This corresponds to $4425/kW for a 50-MW plant
The three sources were averaged to estimate a nominal $5015/kW installed cost for parabolic-trough solar-thermal plants at 50-MW$_e$ rated capacity. Thus, the final installed cost is given by:

$$Installed\ Cost_{STE\ (\$2009/kW)} = \$5015 \cdot 4.255 \cdot \ln(Capacity_{STE})^{-1.035} \quad (20)$$

For O&M costs, an estimated cost of $67,130/MW-year (Stoddard et al. 2006) was converted to $73,836/MW-year in $2009, and $85,856/MW-year, when adjusted to a plant size of 50 MW, using Equation 19. Thus, the equation for O&M costs became

$$Annual\ O\&M\ Costs_{STE\ (\$2009/MW)} = \$85{,}856 \cdot 4.255 \cdot \ln(Capacity_{STE})^{-1.035} \quad (21)$$

5.3.4 – Land Costs

Because the proposed communities are intended to be close to urban centers, the additional land required for the community energy systems in the NZE community scenarios generally constitutes a significant fraction of the overall cost of the generated electricity. To estimate the cost of the land to the community, all of the plots of land for sales greater than 10 acres in size were sampled in the suburbs of each city (Land Watch 2009). Land prices in the outer suburbs that are the most relevant, because this is where the highest potential exists for new community development. The land value that is used in the economic analysis was the median price per acre from the suburbs of each city (see Table 9 and Table 10.) The median was used, because of the wide range in prices. Land values can often vary more than a full order of magnitude just within one suburb. Thus, the very high-end tracts of land can easily skew the averages, and would not be attractive sites for renewable energy system development.

Table 9: Suburban Land Prices in Chicago, IL; Source: Land Watch (2009)

Chicago Suburb	Land Area (Acres)	Price, $	Price/Acre
Lynwood	20	$1,300,000	$65,000
Lynwood	43.13	$1,200,000	$27,823
Orland Park	11.43	$8,300,000	$726,159
Lynnwood	20	$2,000,000	$100,000
Crystal Lake	12.6	$700,000	$55,556
Crystal Lake	12.5	$700,000	$56,000
Crystal Lake	18.6	$6,800,000	$365,591
Lake Zurich	38	$2,800,000	$73,684
Mundelein	12.1	$3,276,000	$270,744
Mundelein	15.8	$3,936,000	$249,114
Mundelein	18.67	$4,651,000	$249,116
		Mean Price	$203,526
		Median Price	$100,000

Table 10: Suburban Land Prices in Phoenix, AZ Source: Land Watch (2009)

Phoenix Suburb	Land Area (Acres)	Price, $	Price/Acre
Peoria	40.1	$3,800,000	$94,763
Mesa	17.42	$6,900,000	$396,096
Mesa	19.6	$5,100,000	$260,204
Chandler	15	$2,800,000	$186,667
Gilbert	13	$3,000,000	$230,769
Scottsdale	18.4	$2,400,000	$130,435
Scottsdale	12.1	$414,900	$34,289
Scottsdale	11.3	$414,900	$36,717
Scottsdale	20	$3,400,000	$170,000
Scottsdale	12	$1,500,000	$125,000
Scottsdale	19.2	$800,000	$41,667
Scottsdale	17.7	$1,900,000	$107,345
Scottsdale	11.25	$675,000	$60,000
Scottsdale	12.4	$950,000	$76,613
Scottsdale	13.47	$1,500,000	$111,359
Scottsdale	13.94	$1,700,000	$121,951
Scottsdale	17.78	$1,900,000	$106,862
Scottsdale	13.2	$1,000,000	$75,758
Scottsdale	15.2	$1,875,000	$123,355
Surprise	40	$550,000	$13,750
Surprise	12	$1,100,000	$91,667
Surprise	40	$1,500,000	$37,500
Surprise	20	$1,200,000	$60,000
		mean price	$117,077
		median price	$106,862

5.3.5 – Financial Assumptions

The financial analysis estimates all costs to a $/kWh levelized cost of electricity (LCOE). The analysis is performed in constant 2009 dollars, with a real discount rate of 3.0%/year. This is roughly the historic average from 1870-2000 (Girola 2005). Costs for each technology are levelized over the number of years shown in the bold rows of Table 11. The lifetimes used for each technology are the median values found from researchers performing life cycle assessments and technology reviews. The median is used to best represent the most commonly agreed-upon lifetime for each technology.

Table 11: Assumed Lifetime for Technologies Considered in Financial Analysis

Technology	Lifetime, Years	Source
Wind turbine	20	(Vestas Wind Systems 2006)
Wind turbine	20	(Martinez, et al. 2009)
Wind turbine	20	(Crawford 2009)
Wind turbine	20	(Schleisner 2000)
Wind turbine	20	(Krohn 1997)
Wind turbine	20	(Gurzenich et al. 1999)
Wind turbine	30	(Ancona and McVeigh 2001)
Wind turbine lifetime	20	7-study median
Four types of PV modules and accessories	30	(Fthenakis et al. 2008)
Multicrystalline PV module and accessories	30	(Koroneos et al. 2004)
Polycrystalline silicon modules	28	(Stoppato 2008)
Thin film and multicrystalline PV modules and accessories	20	(Pacca et al. 2007)
p-Si photovoltaics	25	(Pehnt 2006)
PV lifetime	28	4-study median
Parabolic trough solar-thermal electric plant	25	(Lechon et al. 2008)
Parabolic trough solar-thermal electric plant	30	(NREL 2003)
Parabolic trough solar-thermal electric plant	30	(EPRI 1997)
Parabolic trough solar-thermal electric plant lifetime	30	3-study median

6. Results

The results of analyzing the two NZE scenarios with various renewable energy options are described in this section.

6.1 Baseline Scenario - a Community of NZE Buildings

As previously mentioned, the two unique cost components of the baseline community are the capital cost of the PV panels to be installed on the individual building roofs and the maintenance costs required to keep the panels clean and in working order. Capital costs are borne by each building owner and governed on the building level by the economy of scale equation presented in Equation 17. O&M costs are a function of the system size and the type of installation, as presented in Section 5.3.1. Table 12 and Table 13 present the sizing of the PV system for each unique building type in Chicago and Phoenix based on the PV electric generation model presented in Section 5.1.1 and the costs associated with each system. Aggregated at the bottom of each chart are the total community costs for capital and O&M, and the corresponding levelized cost of electricity generation (LCOE).

The combined levelized cost of electricity generation from the PV systems of $0.431/kWh for Chicago and $0.331/kWh for Phoenix provide the baseline to which each of the alternative NZE community LCOE's are compared. Phoenix receives 56% more sunlight over the course of the year than Chicago. The net electric generation from the PV panels in Phoenix, however, is only 32% higher than in Chicago, because of the higher temperatures in Phoenix, which reduce the PV cell efficiency. Thus, the cost of rooftop PV electricity generation in Phoenix is about 75% of Chicago's.

6.2 Community-Scale NZE using Wind Turbines

A summary of the details of electricity generation and costs is presented in Table 14 for both NZE community scenarios involving wind turbines. As described in 4.2, in Scenario A, the land required for the wind farm is bought outright and devoted entirely to the wind farm. In Scenario B, land for the wind turbines is leased from nearby farmers or other large private land owners.

Table 12: PV Requirements and Costs for Individual Buildings in Chicago

Building Description	Energy Demand (kWh/Year)	Roof Area Available (sf)	Roof Area Required to meet NZE (sf)	Fraction of Demand Met (%)	Net Zero: PV Capacity (kW)	Installed Cost ($/Watt)	Installed Cost ($ 2009)	O&M Costs ($ 2009/yr)
Tall Office	717,688	18,020	51,851	35	251.41	$6.73	$1,692,246	$4,447
Tall Office	717,688	18,020	51,851	35	251.41	$6.73	$1,692,246	$4,447
Medium Office 1	284,558	4,619	5,316	87	64.44	$7.20	$463,640	$1,140
Small Office 1	73,577	2,477	2,851	87	34.56	$7.42	$256,368	$611
Small Office 2	39,461	17,862	20,558	87	249.21	$6.73	$1,678,133	$4,409
Small Office 3	116,423	7,308	8,411	87	101.96	$7.04	$717,320	$1,804
Small Office 4	247,726	15,550	17,897	87	216.95	$6.78	$1,470,877	$3,838
Small Office 5	226,856	14,240	16,390	87	198.67	$6.81	$1,352,785	$3,515
Small Office 6	108,378	6,803	7,830	87	94.91	$7.06	$670,099	$1,679
Small Office 7	63,724	4,000	4,604	87	55.81	$7.25	$404,389	$987
Small Office 8	45,435	5,704	3,283	100	45.80	$7.32	$335,085	$810
Sporting Goods	61,410	9,756	4,437	100	61.90	$7.21	$446,262	$1,095
Convenience	35,692	3,132	2,579	100	35.98	$7.40	$266,358	$636
Strip Mall:	10,701	1,700	773	100	10.79	$7.85	$84,713	$191
Strip Mall:	10,701	1,700	773	100	10.79	$7.85	$84,713	$191
Strip Mall: Nail	10,701	1,700	773	100	10.79	$7.85	$84,713	$191
Strip Mall:	10,701	1,700	773	100	10.79	$7.85	$84,713	$191
Strip Mall: Gas	56,651	9,000	4,093	100	57.10	$7.24	$413,311	$1,010
Strip Mall: Dry	10,701	1,700	773	100	10.79	$7.85	$84,713	$191
Strip Mall:	10,701	1,700	773	100	10.79	$7.85	$84,713	$191
Strip Mall:	18,884	3,000	1,364	100	19.03	$7.64	$145,390	$337
Strip Mall: Bank	56,651	9,000	4,093	100	57.10	$7.24	$413,311	$1,010
Strip Mall:	113,958	10,000	8,233	100	114.87	$6.99	$803,414	$2,032
Strip Mall:	34,187	3,000	2,470	100	34.46	$7.42	$255,671	$610
Strip Mall: Café	42,598	3,000	3,078	97	41.86	$7.35	$307,598	$740
Strip Mall:	42,598	1,700	1,744	97	23.72	$7.56	$179,225	$420
Strip Mall:	24,139	3,000	3,078	97	41.86	$7.35	$307,598	$740
Strip Mall:	31,949	2,250	2,308	97	31.39	$7.45	$233,973	$555
Strip Mall:	110,046	7,750	7,950	97	108.13	$7.02	$758,519	$1,913
Interfaith	58,344	15,000	4,215	100	58.81	$7.23	$425,050	$1,040
High School	890,009	80,000	64,300	100	897.11	$6.32	$5,673,492	$15,870
Middle School	333,753	90,000	24,113	100	336.42	$6.64	$2,232,308	$5,951
Elementary	259,586	70,000	18,754	100	261.66	$6.72	$1,757,753	$4,629
Elementary	259,586	70,000	18,754	100	261.66	$6.72	$1,757,753	$4,629
Community	157,495	37,000	11,378	100	158.75	$6.88	$1,092,893	$2,808

Building Description	Energy Demand (kWh/Year)	Roof Area Available (sf)	Roof Area Required to meet NZE (sf)	Fraction of Demand Met (%)	Net Zero: PV Capacity (kW)	Installed Cost ($/Watt)	Installed Cost ($ 2009)	O&M Costs ($ 2009/yr)
Village Center 1	21,283	5,000	1,538	100	21.45	$7.59	$162,906	$380
Village Center 2	21,283	5,000	1,538	100	21.45	$7.59	$162,906	$380
Village Center 3	21,283	5,000	1,538	100	21.45	$7.59	$162,906	$380
Typical	3,248	1,015	171	100	2.91	$8.37	$24,392	$216
Typical	2,784	768	147	100	2.50	$8.44	$21,069	$185
Typical	3,476	408	183	100	3.12	$8.35	$26,018	$231
Community	13,996,908	2,207,405	841,953	92.1%	12044	$7.81	$94,025,758	$649,367
LCOE ($/kWh)							$0.3847	$0.0464
							Total LCOE:	$0.4311

Table 13: Requirements and Costs for Individual Buildings in Phoenix

Building Description	Energy Demand (kWh/Year)	Roof Area Available (sf)	Roof Area Required to meet NZE (sf)	Fraction of Demand Met (%)	Net Zero: PV Capacity (kW)	Installed Cost ($/Watt)	Installed Cost ($ 2009)	O&M Costs ($ 2009/yr)
Tall Office Building 1	560,880	18,020	30,480	59	251.41	$6.73	$1,692,246	$4,447
Tall Office Building 2	560,880	18,020	30,480	59	251.41	$6.73	$1,692,246	$4,447
Medium Office 1	222,385	4,619	3,125	100	43.60	$7.33	$319,758	$771
Small Office 1	57,501	2,477	1,676	100	23.38	$7.56	$176,809	$414
Small Office 2	30,839	17,862	12,085	100	168.61	$6.86	$1,157,353	$2,983
Small Office 3	90,986	7,308	4,945	100	68.99	$7.17	$494,712	$1,220
Small Office 4	193,600	15,550	10,521	100	146.79	$6.91	$1,014,416	$2,597
Small Office 5	177,290	14,240	9,635	100	134.42	$6.94	$932,971	$2,378
Small Office 6	84,698	6,803	4,603	100	64.22	$7.20	$462,145	$1,136
Small Office 7	49,801	4,000	2,706	100	37.76	$7.39	$278,894	$668
Small Office 8	35,508	5,704	1,930	100	26.92	$7.51	$202,175	$476
Sporting Goods	60,822	9,756	3,305	100	46.11	$7.31	$337,294	$816
Convenience Store	57,602	3,132	3,130	100	43.67	$7.33	$320,289	$773
Strip Mall: Karate	10,598	1,700	576	100	8.04	$7.97	$64,028	$142
Strip Mall: Liquor	10,598	1,700	576	100	8.04	$7.97	$64,028	$142
Strip Mall: Nail Salon	10,598	1,700	576	100	8.04	$7.97	$64,028	$142
Strip Mall: Barber	10,598	1,700	576	100	8.04	$7.97	$64,028	$142
Strip Mall: Gas	56,109	9,000	3,049	100	42.54	$7.34	$312,389	$753
Strip Mall: Dry	10,598	1,700	576	100	8.04	$7.97	$64,028	$142
Strip Mall: Parcel	10,598	1,700	576	100	8.04	$7.97	$64,028	$142

Building Description	Energy Demand (kWh/Year)	Roof Area Available (sf)	Roof Area Required to meet NZE (sf)	Fraction of Demand Met (%)	Net Zero: PV Capacity (kW)	Installed Cost ($/Watt)	Installed Cost ($ 2009)	O&M Costs ($ 2009/yr)
Strip Mall: Pharmacy	18,703	3,000	1,016	100	14.18	$7.75	$109,889	$251
Strip Mall: Bank	56,109	9,000	3,049	100	42.54	$7.34	$312,389	$753
Strip Mall: Organic	183,913	10,000	9,995	100	139.44	$6.93	$966,087	$2,467
Strip Mall: Seafood	55,174	3,000	2,998	100	41.83	$7.35	$307,439	$740
Strip Mall: Café	24,834	3,000	1,350	100	18.83	$7.64	$143,900	$333
Strip Mall:	24,834	1,700	765	100	10.67	$7.86	$83,844	$189
Strip Mall:	14,073	3,000	1,350	100	18.83	$7.64	$143,900	$333
Strip Mall:	18,626	2,250	1,012	100	14.12	$7.75	$109,457	$250
Strip Mall:	64,155	7,750	3,486	100	48.64	$7.30	$354,849	$860
Interfaith Worship	137,362	15,000	7,465	100	104.15	$7.03	$731,949	$1,842
High School	1,004,311	80,000	54,578	100	761.47	$6.38	$4,854,509	$13,470
Middle School	376,616	90,000	20,467	100	285.55	$6.69	$1,910,069	$5,051
Elementary School 1	292,924	70,000	15,919	100	222.09	$6.77	$1,504,017	$3,929
Elementary School 2	292,924	70,000	15,919	100	222.09	$6.77	$1,504,017	$3,929
Community	241,237	37,000	13,110	100	182.91	$6.84	$1,250,470	$3,236
Village Center 1	32,600	5,000	1,772	100	24.72	$7.54	$186,395	$437
Village Center 2	32,600	5,000	1,772	100	24.72	$7.54	$186,395	$437
Village Center 3	32,600	5,000	1,772	100	24.72	$7.54	$186,395	$437
Typical Detached	4,768	1,015	190	100	3.24	$8.33	$27,000	$240
Typical Townhouse	3,657	768	146	100	2.49	$8.44	$20,977	$184
Typical Apartment	5,086	408	203	100	3.46	$8.30	$28,708	$256
Community Totals	17,674,273	2,207,405	780,528	97.4%	12075	$7.89	$95,211,15	$690,852
LCOE ($/kWh)							$0.2920	$0.0391
							Total	$0.3310

Table 14: Generation and Cost Details for a NZE Community using Wind Power

	Chicago	Phoenix
Community Electric Demand (kWh/yr)	13,996,908	17,674,273
Capacity Factor	0.3600	0.1195
Required Capacity (MW)	4.44	16.88
1.5 MW Turbines Required	3	12
Capital Cost - Turbines	$8,617,500	$34,470,000
O&M Cost Turbines ($/yr)	$229,191	$241,458
Acres Required (Scenario A)	141.2	564.7
Land Cost (Scenario A)	$14,117,647	$60,345,398
Acres Required (Scenario B)	1.5	6
Land Rental Cost (Scenario B), $/yr	$120,000	$769,404
Extra Generation (kWh/yr)	195,534	1,172,854
Sale of Extra Electricity ($/yr)	$11,537	$76,236
LCOE (Capital)	$0.0409	$0.1297
LCOE (O&M)	$0.0164	$0.0137
LCOE (Land, Scenario A)	$0.0671	$0.2270
LCOE (Land, Scenario B)	$0.0129	$0.0435
LCOE (Sale of Extra Electricity)	-$0.0008	-$0.0043
LCOE Total, Scenario A	$0.1236	$0.3661
LCOE Total, Scenario B	$0.0694	$0.1826

To generate the community's 14 million kWh in Chicago using wind power at the calculated capacity factor of 0.360 requires 4.44 MW of installed capacity. Because this capacity comes in discrete, 1.5-MW increments, the community must purchase three 1.5-MW turbines at a levelized capital cost of 4.09 cents/kWh. The sale of the electricity from the extra 60 kW of rated capacity represents a negligible contribution to the LCOE. In Chicago, the levelized O&M costs of the wind farm are about 40% of the magnitude of the capital costs. Using leased land for the turbines, the total cost of generated electricity comes out to only about 7 cents/kWh. If instead, all the land is bought outright (in the relatively expensive suburbs of Chicago) the levelized cost of electricity generation would be 5.4 cents/kWh higher (12.4 cents/kWh, compared to 7 cents/kWh).

For Phoenix, the wind turbine scenarios suffer from a very low capacity factor, brought about simply by a lack of consistent wind. Indeed, it would make little sense to build wind turbines in Phoenix proper, which has a wind class rating of 1 (poor), while there are very good potential wind sites on the ridgelines of the mountains 25-50 miles east of the city. Thus, for Phoenix, the capacity factor is three times lower than Chicago's (0.120), and the levelized capital cost is three times higher, because there is no economy of scale cost benefit for building the larger number of turbines required. Despite having four times as many turbines, the levelized O&M cost in Phoenix is calculated as being lower than in Chicago. This is mainly for one reason: wind turbine O&M costs are typically reported per MWh of generation, as in Wiser and Bolinger (2009), rather than per MW of installed capacity; yet the economy of scale curve for O&M is based on MW of installed capacity. Thus, Phoenix benefits from an O&M standpoint, relative to Chicago, from having a large field of unproductive turbines. There is a good argument for why O&M costs should be a function of generated energy rather than being a per-turbine rate (which would be the case if they were reported as per MW of installed capacity). Turbines subject to lower wind speeds would be expected to have lower component failure rates because of lower mechanical stresses and lower electric loads on the power equipment. With four times the land area required for both land acquisition scenarios and comparable land prices for Phoenix as for Chicago, the cost of the total required land ends up being about four times higher for the community in Phoenix. Using leased land, the LCOE of electric generation for Phoenix is 18.3 cents/kWh, but using purchased land, the cost doubles to 36.6 cents/kWh.

6.3 Community-Scale NZE using a Solar-Thermal Electric Parabolic Trough Plant

A summary of the details of electricity generation and costs is presented in Table 15 for the NZE community scenarios, using a solar-thermal parabolic trough plant.

Table 15: Generation and Cost details for a NZE Community using a Solar Thermal Electric Plant

	Chicago	Phoenix
Community Electric Demand (kWh/yr)	13,996,908	17,674,273
Capacity Factor	0.106	0.248
Overall Plant Efficiency	0.0989	0.1164
Required Capacity (MW)	15.04	8.12
Capital Cost - Solar Thermal Plant	$102,826,484	$63,734,729
O&M Costs ($/year)	$1,494,547	$806,896
Acres Required	78.6	42.5
Land Cost	7,859,746	4,537,592
LCOE (capital)	$0.4183	$0.2336
LCOE (O&M)	$0.1203	$0.0514
LCOE (land)	$0.0284	$0.0130
LCOE(total)	$0.5670	$0.2980

The solar-thermal electric parabolic trough plant is most economical in Phoenix, which receives ample direct sunlight. There, the plant operates at a capacity factor of around 25%. Chicago, on the other hand, receives less than half of the direct sunlight that Phoenix does, and its capacity factor is just over 10%. The plant in Chicago is further hindered by frequent part-load operation at lower turbine inlet steam temperatures, which reduces the plant’s efficiency. The Schott Company recommends a plant size of 150 to 200 MW to fully take advantage of the economy of scale for solar-thermal power plants (Schott 2004). The required plant size for the community studied here is over an order of magnitude smaller, and for both locations, solar-thermal suffers from a high capital cost. For the case of Phoenix, with a very small 8.1-MW plant, the estimated capital cost is $7750/kW installed. For Phoenix, the capital cost represents just over 75% of the levelized cost of electricity generated, with O&M representing about 20%, and land representing the remaining 5 %. To make solar-thermal electricity the most economic solution, however, the size of the community must be scaled up (see Section 6.6).

6.4 Community-Scale NZE using a PV Farm

A summary of the details of electricity generation and costs is presented in Table 16Table 16 for the NZE community scenarios, using a PV farm.

Table 16: Generation and Cost Details for a NZE Community using a PV Farm

	Chicago	Phoenix
Community Electric Demand (kWh/yr)	13,996,908	17,674,273
Capacity Factor	0.1273	0.1679
Overall AC Efficiency	0.104	0.093
Required Capacity (MW)	12.55	12.01
Capital Costs - Solar PV farm	$69,757,146	$66,909,100
O&M Costs ($/year)	$78,956	$75,569
Acres Required	50.8	48.6
LCOE (capital)	$0.2631	$0.1998
LCOE (O&M)	$0.0056	$0.0043
LCOE (land)	$0.0191	$0.0155
LCOE(total)	$0.2879	$0.2196

Capital costs for the PV farm are almost 30% lower than the capital costs in the NZE building PV scenario. O&M costs are dramatically lower for the PV farm. This scenario provides a very concrete example of how cost savings can be achieved through economies of scale. Instead of planning, installing, and grid-wiring thousands of individual PV systems, the same energy can be generated through one large installation. Instead of maintenance taking place at thousands of different facilities, each requiring roof access for maintenance personnel and their cleaning equipment, cleaning can be handled en masse, and possibly even automated. The only tradeoff is that new land is required for the PV farm, as opposed to the already-developed roof area in the NZE building scenario.

6.5 Cost Comparison

The LCOE for each NZE approach for both cities is summarized in Figure 13. The relative costs from the base case of the community of NZE buildings to each of the NZE communities are labeled above the bars for each NZE community scenario. In Chicago, the community-scale NZE scenario using wind turbines is the least expensive, with a levelized cost of electricity generation that is between 71% and 84% less than the nZEB scenario, the precise difference depending on how the land is acquired. For Phoenix, despite its poor capacity factor, wind power is still the least expensive option at this scale, when the required land is leased, rather than purchased. Otherwise, building a solar-photovoltaic farm is the most economical choice for the community.

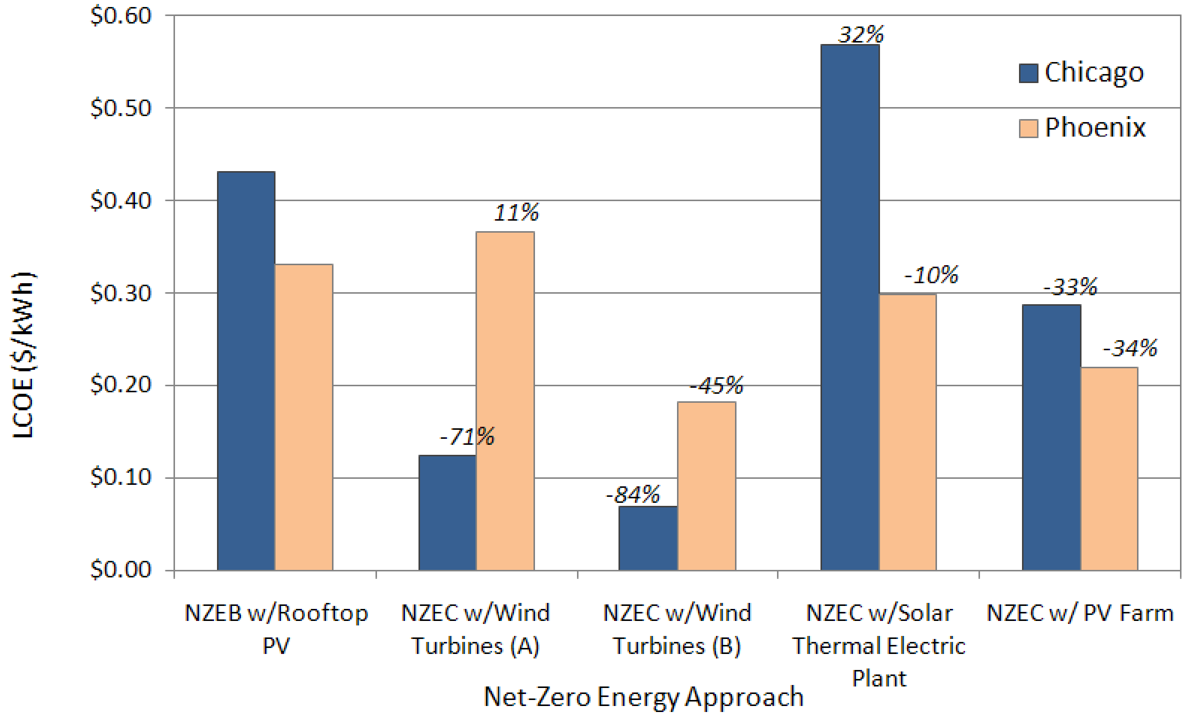

Figure 13: LCOE for Each NZE Approach

6.6 Scaling the Community

The analysis presented thus far is valid only for the case of a specific community size. In this section, the relative costs of each scenario across a broad spectrum of community sizes are examined. The selected community was scaled linearly, for this purpose. For example, a community of twice as many people was assumed to have twice as many of each building. The general makeup of the community, however, was assumed to remain the same. The levelized cost of electricity generation for each technology is presented in Figure 14 and Figure 15 for community sizes ranging from 1,000 to 100,000 people.

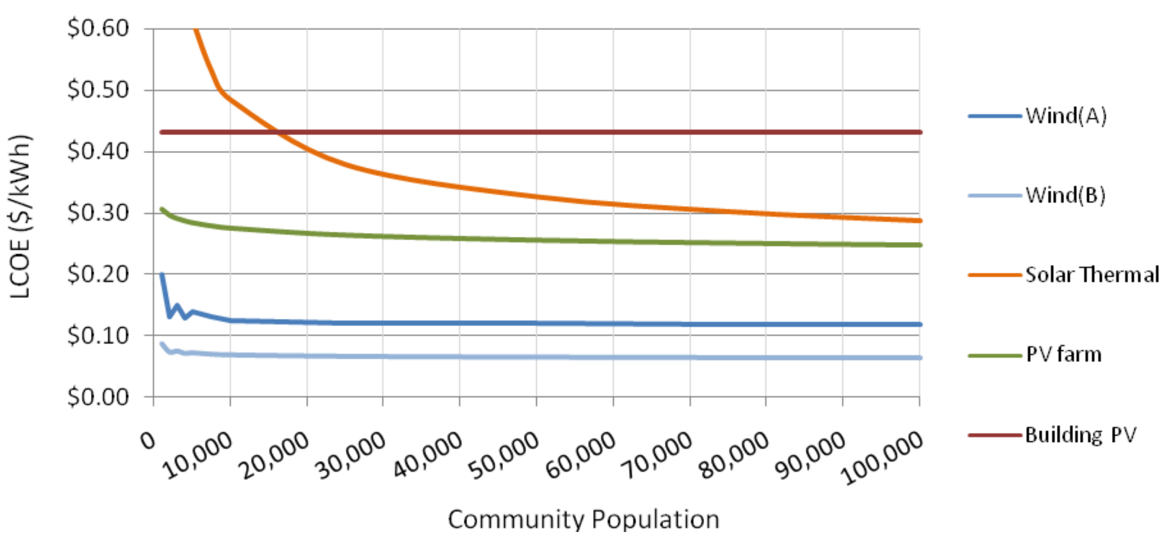

Figure 14: LCOE in Chicago for Each Scenario as a Function of Community Size

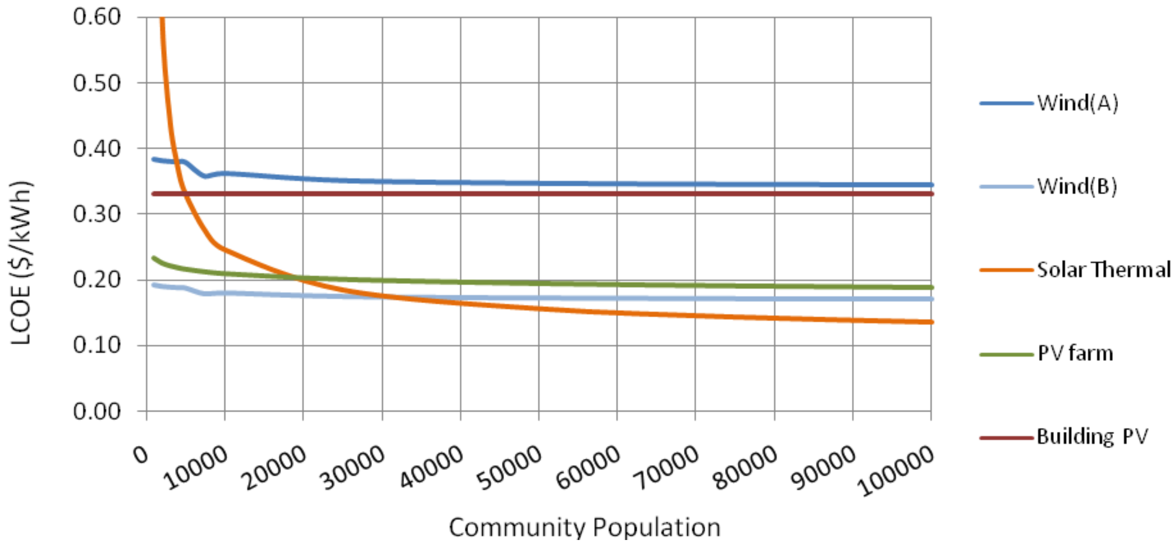

Figure 15: LCOE in Phoenix for Each Scenario as a Function of Community Size

The community of NZE buildings receives no cost benefit as the city is scaled up, because each building is its own entity, from an energy generation standpoint, and no economies of scale exist because individual PV systems are still sized identically and cost the same for a given building.

The wind power cost very gradually decreases as the community size increases towards the size of a small city. This is attributed to a decrease in the O&M costs. There is some erratic behavior in the LCOE for wind at small community sizes because of the requirement for a discrete number of wind turbines. This results, at very small community sizes, from one or two 1.5-MW wind turbines producing significantly more electricity than the community consumes. All of the costs for a full turbine are borne by the small community, and the electricity from the excess generation is sold at a wholesale rate that is below the cost of generation. Thus, the net effect is an LCOE for the community that is significantly higher than for a community ideally sized for a discrete number of wind turbines. An obvious alternative for those communities where the turbine is oversized would be to install a smaller wind turbine, but these smaller turbines are subject to economies of scale that would also lead to a more expensive generation cost than that of a larger community. For Chicago, at any community size, and for either land acquisition scenario, however, the community using wind power has costs far smaller than for any of the other scenarios. As the community size increases, the LCOE for wind power using leased land approaches a rate that is almost only about one sixth the LCOE for the individual NZE building case, using rooftop PV.

In Phoenix, however, the situation is less clear. Wind generated electricity using leased land remains the least expensive scenario up to a community size of 30,000 people (which would at that point constitute a small city). Above that size, community-scale NZE using a parabolic trough solar-thermal electric plant becomes the least expensive option. Solar-thermal electric becomes more competitive than a solar PV farm for NZE communities with more than 18,000 people.

For Chicago, individual building NZE using rooftop PV is the most expensive scenario for community sizes over 16,000 people, and for Phoenix, it ranges from between 60% and 120% more expensive than the lowest cost NZE community option.

6.7 Community-Wide NZE

NZE communities, using any of the scenarios presented in this paper or combination thereof, should be readily able to achieve 100% NZE status through a scaling of the energy generation system(s). Restrictions on NZE status for community-scale NZE would only come into play if there were restrictions on the available land area. For the same community of NZE buildings, however, achieving 100% NZE status for the entire community is much more difficult, especially if those buildings use only rooftop PV for electricity generation. Figure 16 shows the fraction of community-wide NZE status that is achievable, given a wide range of reductions in building energy consumption of the community's HP buildings, compared to RECS (2005) and CBECS (2003). At 30% reduction levels, the communities in Chicago and Phoenix are 80% and 84% NZE, respectively. At 50%, they are 85% and 94% NZE, and at 70%, as assumed in this report, they are 92% and 97% NZE.

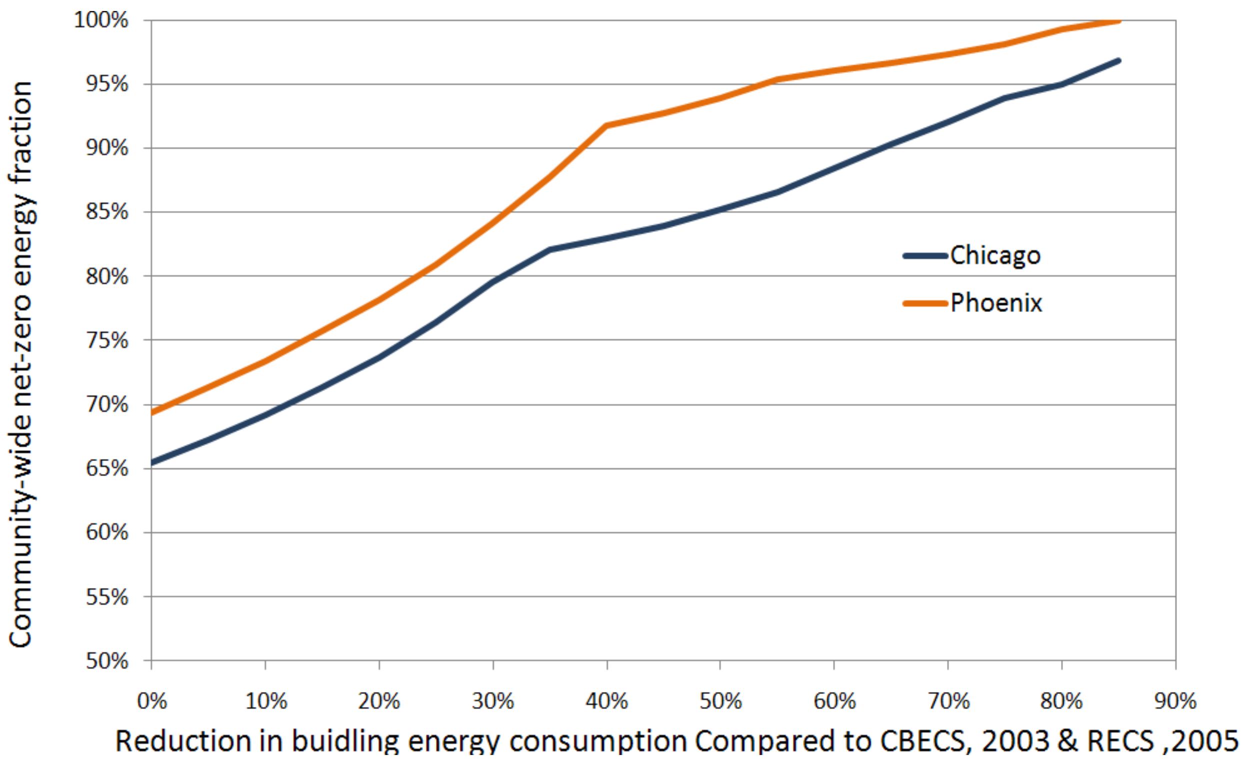

Figure 16: Community-Wide NZE Fraction for the nZEBs Scenario using only Rooftop PV

7. Discussion and Conclusions

As mentioned in Section 6.5, for either city, the NZE building scenario using rooftop photovoltaics was the most expensive scenario. For Chicago, however, the LCOE for rooftop PV is about equal to the LCOE for solar-thermal electricity for a community size of 16,000 people. This is an interesting result, because according to conventional thinking, while not optimally suited for Chicago, rooftop PV would still be a viable technology for those building owners looking to 'go green'. That same conventional thinking, however, would dictate that a solar-thermal plant is a ridiculous idea in a place like Chicago. In reality, however, the costs can be nearly equivalent for powering a NZE community in Chicago for these two technologies. Similarly for Phoenix, in the Arizona desert, it would seem almost criminal to suggest wind power over solar power. Yet, at the default community size, the case of the wind farm on leased land, as inefficient as the wind generation may be, is still more cost-effective than either solar-thermal electric generation or a PV farm at the default community size (let alone rooftop PV, which is more expensive still).

Thus, one could argue that conventional thinking may have a bias towards the idea of a nZEB and/or a lack of appreciation for economies of scale. Furthermore, there may be an automatic assumption that a having one more favorable renewable resource endowment means that the most cost-effective solution must utilize that resource. The bias towards nZEBs may have something to do with the idea of liberating the building from external sources of generation, but in a technical sense, this is not true, because NZE buildings are still very much dependent on the grid.

Phoenix was chosen for this study because it has such abundant solar resources, and poor wind resources, making it one of the most attractive places for NZE buildings using PV. Thus, what has been shown in this study is that even for the best case in the U.S. for NZE buildings, there are more cost-effective approaches to achieving NZE than the conventional suite of technologies (rooftop PV, with aggressive energy-efficiency measures) used at the building level. By expanding the conceptual boundary for net-zero, a community can take better advantage of economies of scale, as well as having other generation options at its disposal.

7.1 Advantages and Disadvantages of the two Concepts

While the cost comparison presented in this paper provides a compelling comparison between the community of NZE buildings and various NZE communities, it does not tell the whole story. Table 21 lists advantages and disadvantages of the NZE building approach versus the NZE community approach. This list covers some practical considerations that don't fit into an economic analysis, some economic effects outside of the bounds of the analysis given in this paper, and some factors that may affect whether the NZE status is actually achieved in practice.

Table 17: Advantages and Disadvantages of nZEBs versus ZNE Communities

	Advantages	Disadvantages
Community-Scale NZE	- Higher capacity factors possible with wind power and solar-thermal electric, compared to solar PV - Likely more attractive from a utility standpoint to interface one or two generating facilities with the grid, than to have thousands of small generators grid-tied	- For the case of wind turbines, there may be some "Not in My Backyard" response in regard to noise or aesthetics. - Would likely entail a suboptimal geographic placement of large scale generation, which may be better suited for more marginal, yet cheaper land, with better wind or solar resource.
Building-Scale NZE	- Residential and commercial building owners may become more conscious of energy use and try to conserve - New jobs within the community created in businesses providing PV cleaning and repair services	- Would require that trees and other sources of shading not interfere with or foul the surface of the solar panels. This could lead to aesthetic/quality of life issues. - Places responsibility of O&M into the hands of average citizens who may be ignorant of, apathetic towards, or otherwise unable to pay for regular maintenance - Limitations on generation for communities subject to frequent dust or snowstorms - Becomes less 'NZE' over time as PV system ages.

7.2 Issues Requiring Further Analysis

How would this analysis change if learning curves were taken into account? Is one technology likely to surpass another in price over time because of technology improvements or the transition to more cost-optimized mass production?

How do the economics work out for the NZE community with dynamic electricity rates or different buy vs. sell rate? In these communities, solar technologies' preferential generation of electricity during peak hours may make its revenues from the grid higher than its purchases from the grid, thus decreasing their LCOE, compared to wind.

How would the lack of availability of significant land affect the results?

How would the economics of NZE communities change with differential selling and purchasing rates of electricity to and from the local utility?

How would adding storage (both thermal and electric) affect the economics because high penetration of NZE buildings/communities will likely create problems with the electric transmission and distribution system without storage?

How will incentives affect the economics?

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Appendices A: Validation of Results Using Renewable Energy Packaged Tools

To validate the results from this study, two packaged software tools developed by NREL were used to estimate the LCOE for each of the different scenarios. The first of the two software tools is HOMER, (Homer: The Optimization Model for Distributed Power, 2009) NREL's optimization model for distributed power. Homer is set up to investigate design options for both off-grid and grid-connected power systems, using both renewable and fossil-fuel-based generation. To simulate the proposed NZE community scenarios, a grid-connected system using the renewable-technology system of interest was modeled, in both Chicago and Phoenix, and the generation was sized (based on the results from a preliminary 'guess' run) so that the excess electricity sold to the grid would be equal to the electricity purchased from the grid. Rates of sold and purchased electricity were set equal to one another, and constant at all times. For the NZE building scenario, two model runs were performed; one for the aggregate of the community's residential buildings, with the solar panels at a 35° tilt, and one for the aggregate of the community's commercial buildings, with no tilt. The LCOE for the community was estimated as the average of the two, weighted by the kWh generated by each sector. Figure A- 1 and Figure A- 2 show model inputs for PV and wind power systems, respectively. The model inputs shown for PV were for the PV farm community-scale NZE scenario. The specifications for the wind turbine and the PV panel were the same as those used in this report. Costs were also estimated based on the methodology presented in this report, because they are expected as inputs. Because the costs and the financial structures used in HOMER were the same as those used in this report, this analysis basically served as a verification of the PV and wind energy production models used in this report.

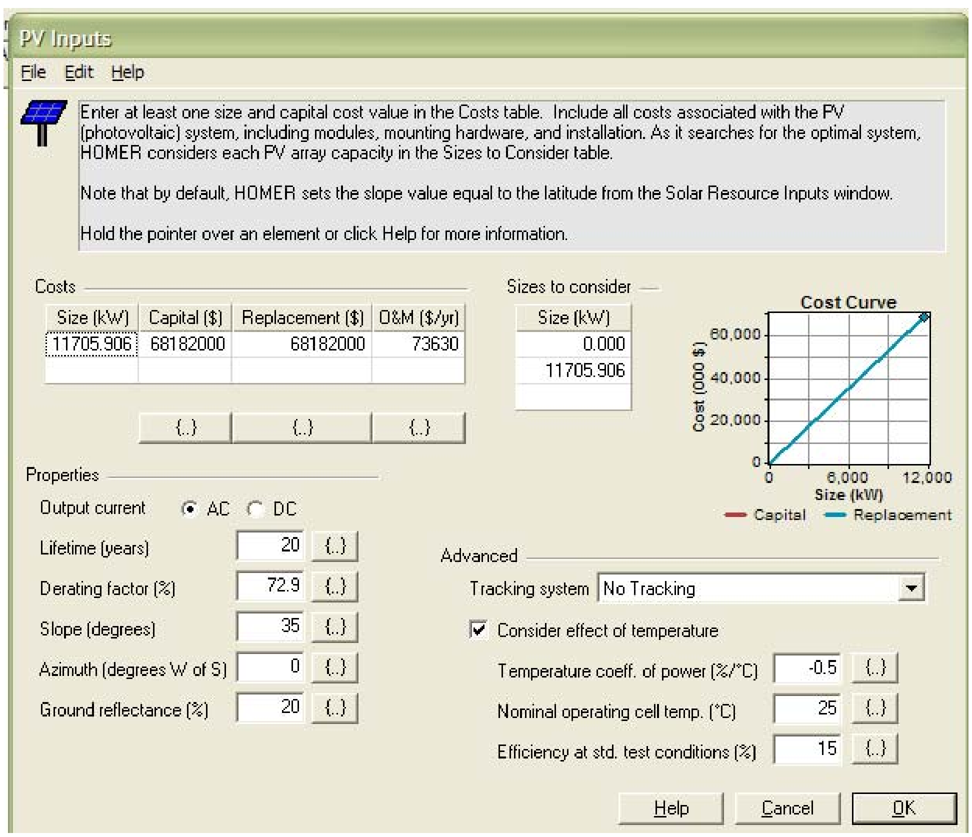


Figure A- 1: HOMER Screenshot of PV Inputs Used for the PV Farm NZE Community Scenario

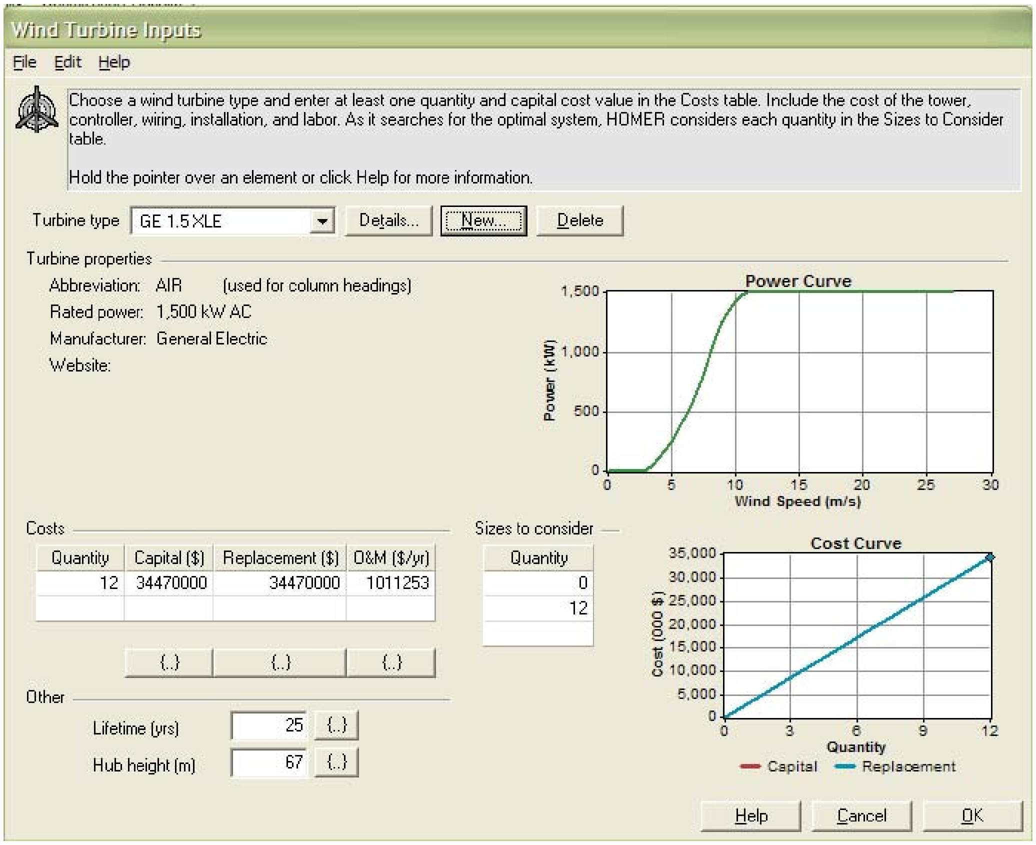
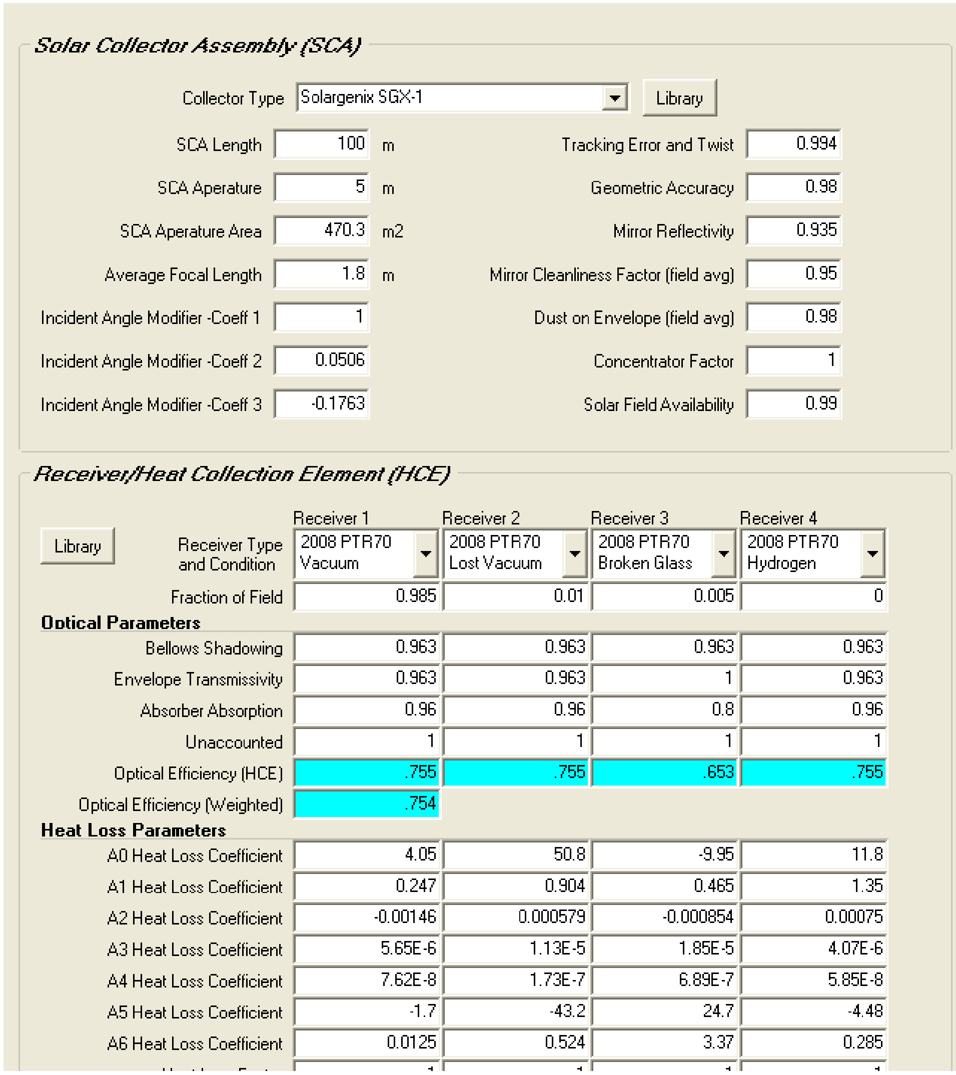


Figure A- 2: HOMER Screenshot of Wind Power Inputs used for the Wind Turbine (B) Scenario in Phoenix

The second software tool used for validation was the Solar Advisor Model (Solar Advisor Model, 2009) developed by NREL. SAM is tool designed to evaluate the cost of electricity production for all types of solar energy systems. SAM takes in very detailed inputs for the solar generation system as well as detailed inputs for cost breakdowns and financial parameters. For certain technologies, the program also only allows certain industry-standard financial structures not considered in this report. With this in mind, the program was used in two ways. First, SAM's generation model was used to externally estimate an LCOE, based on the costs and the financial structure presented in this report. The details of the power generation system were specified as laid out in this report. Many generation parameters, however, such as inverter performance curves in the case of PV systems, and optical parameters of the collector in the case of the solar-thermal plant were not known or specified in this report, so the default values were used. A screenshot of the generation parameters for PV and parabolic troughs is shown in Figure A- 3 and Figure A- 4, respectively. Much like the approach taken for the HOMER model, a weighted average of residential and commercial PV system LCOE was to estimate the cost of the NZE building scenario.

Figure A- 3: SAM Screenshot of PV Generation Parameters



Solar Collector Assembly (SCA)

Collector Type: Solargenix SGX-1 — Library

SCA Length	100	m	Tracking Error and Twist	0.994
SCA Aperature	5	m	Geometric Accuracy	0.98
SCA Aperature Area	470.3	m2	Mirror Reflectivity	0.935
Average Focal Length	1.8	m	Mirror Cleanliness Factor (field avg)	0.95
Incident Angle Modifier -Coeff 1	1		Dust on Envelope (field avg)	0.98
Incident Angle Modifier -Coeff 2	0.0506		Concentrator Factor	1
Incident Angle Modifier -Coeff 3	-0.1763		Solar Field Availability	0.99

Receiver/Heat Collection Element (HCE)

Library	Receiver 1	Receiver 2	Receiver 3	Receiver 4
Receiver Type and Condition	2008 PTR70 Vacuum	2008 PTR70 Lost Vacuum	2008 PTR70 Broken Glass	2008 PTR70 Hydrogen
Fraction of Field	0.985	0.01	0.005	0
Optical Parameters				
Bellows Shadowing	0.963	0.963	0.963	0.963
Envelope Transmissivity	0.963	0.963	1	0.963
Absorber Absorption	0.96	0.96	0.8	0.96
Unaccounted	1	1	1	1
Optical Efficiency (HCE)	.755	.755	.653	.755
Optical Efficiency (Weighted)	.754			
Heat Loss Parameters				
A0 Heat Loss Coefficient	4.05	50.8	-9.95	11.8
A1 Heat Loss Coefficient	0.247	0.904	0.465	1.35
A2 Heat Loss Coefficient	-0.00146	0.000579	-0.000854	0.00075
A3 Heat Loss Coefficient	5.65E-6	1.13E-5	1.85E-5	4.07E-6
A4 Heat Loss Coefficient	7.62E-8	1.73E-7	6.89E-7	5.85E-8
A5 Heat Loss Coefficient	-1.7	-43.2	24.7	-4.48
A6 Heat Loss Coefficient	0.0125	0.524	3.37	0.285

Figure A- 4: PV Generation Parameters used in SAM

The second way that SAM was used was to investigate the overall sensitivity of the assumed generation and cost parameters, as well as the financial structure used in this report on the LCOE, by comparing them to the default values used in SAM, which are intended to be typical, but not necessarily representative of the exact scenario laid out in this report (an example being the use of a utility power purchase agreement, and bank loans). In this analysis, the plant size, solar field orientation, and the specific solar panel model were specified, with the rest of the parameters left as default. All state and federal incentives, however, were removed.

Table A1 summarizes the LCOE's calculated from each program, using all of the described approaches, and compared to the baseline methodology used in this report, for Chicago and Phoenix. In most cases, there is very good agreement between each of the models. It is quite compelling that the LCOE for solar-thermal generation was so similar for the default parameters in SAM, as compared to this report, considering the use of two very different methodologies. For both HOMER and SAM, the generation models themselves predicted very similar size systems for each of the technologies, compared to this report, and thus the LCOE's all came out to be very similar, given the same costs and financial structures.

Table A- 1 ***LCOE comparison using HOMER and SAM***

	Baseline NZE Buildings	NZE Community using Wind (A)	NEZ Community using Wind (B)	NZE Community using Solar Thermal	NZE Community using PV Farm
Current Methodology, Chicago	$0.431	$.124	$.069	$.567	$.282
HOMER[24]*, Chicago	$0.427	$.125	$.071	N/A	$.272
SAM[21]*, Chicago	$.441	N/A	N/A	$0.524	$.292
SAM[21]**, Chicago	$.384	N/A	N/A	$0.552	$.307
Current Methodology, Phoenix	$.331	$.366	$.182	$.298	$.215
HOMER[24]*, Phoenix	$.316	$.371	$.188	N/A	$.201
SAM[21]*, Phoenix	$.315	N/A	N/A	$0.293	$.218
SAM[21]**, Phoenix	$.280	N/A	N/A	$.231	$.230

*Using assumed costs and financial parameters, and using the same financial cost structure described in this report

**Using specified plant size, solar field orientations, and solar panel model with the program's default values for all other financial, cost and generation parameters. Land costs added to the program's results (state and federal incentives removed)